Don’t Give Me the Jitters!

Capturing & characterizing **live Mega-LEO** signals for **Fused** and **Opportunistic LEO GNSS**

TEXAS
The University of Texas at Austin

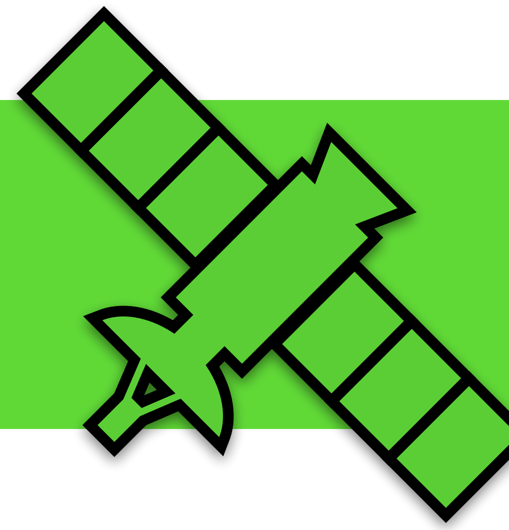
THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY

6G @ UT

Peter A. Iannucci • Todd E. Humphreys • 2021/09/10

Goal

Mega-LEO PNT back-up to GPS



e.g. Starlink, Kuiper; but **Starlink** is live today…

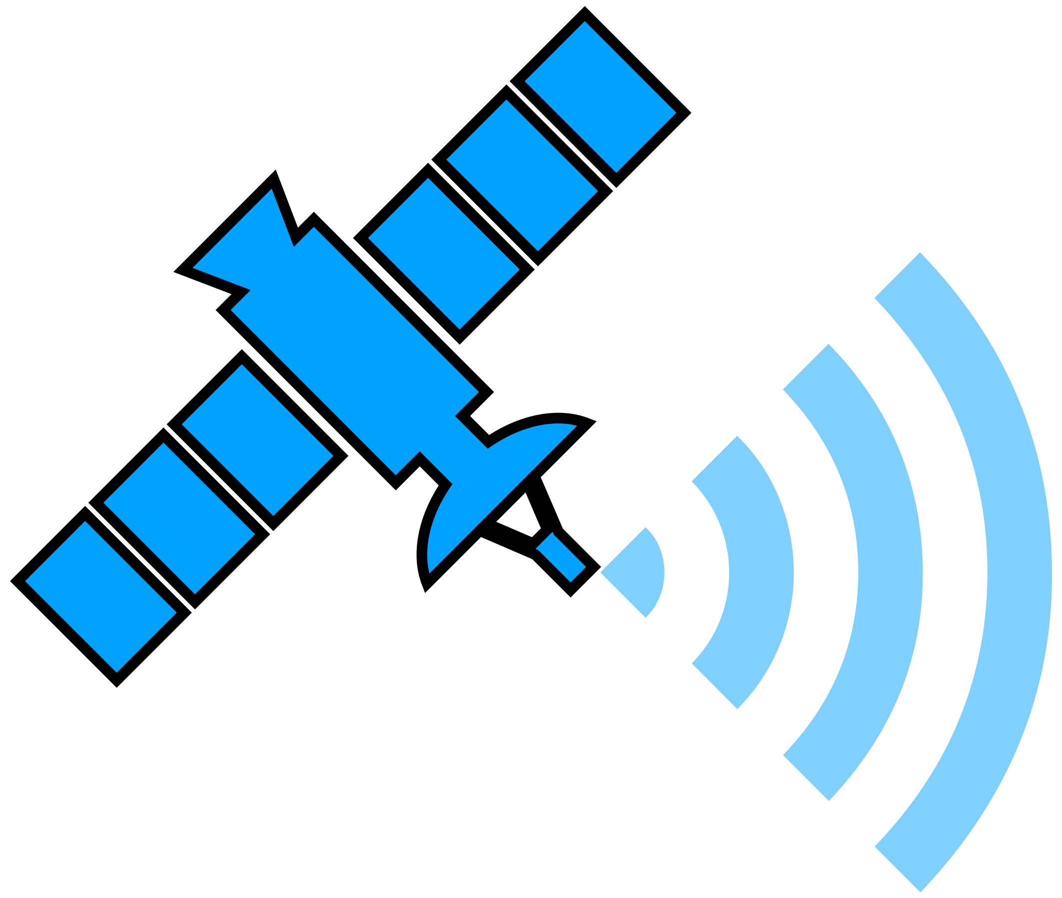
1. Vision for fused LEO PNT
2. Definition of “Timing Jitter”
3. Reverse-engineering Starlink

But these signals are not intended for PNT…
Must assess suitability under fused LEO model!

Use existing comms resources for PNT

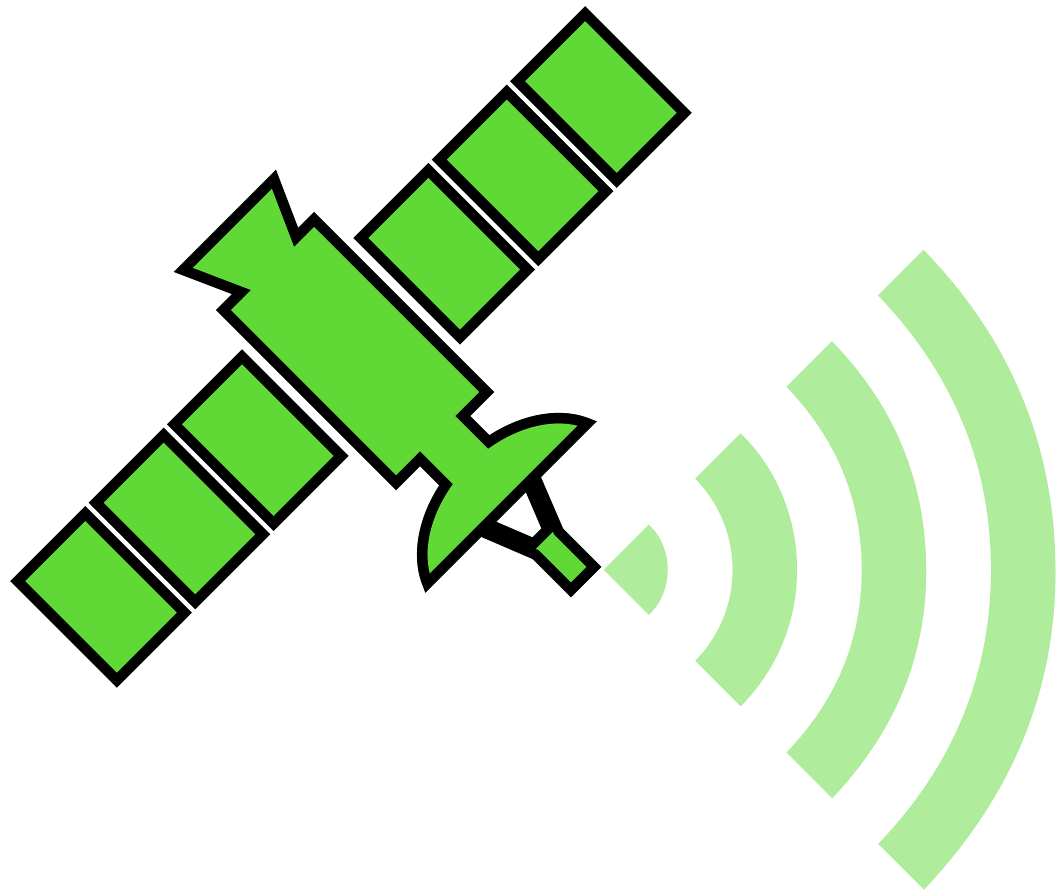
Peter A. Iannucci, Todd E. Humphreys,
Fused Low-Earth-Orbit GNSS.
Preprint, arXiv:2009.12334. September, 2020.

But these signals are not intended for PNT…
Must assess suitability under fused LEO model!



~$500M

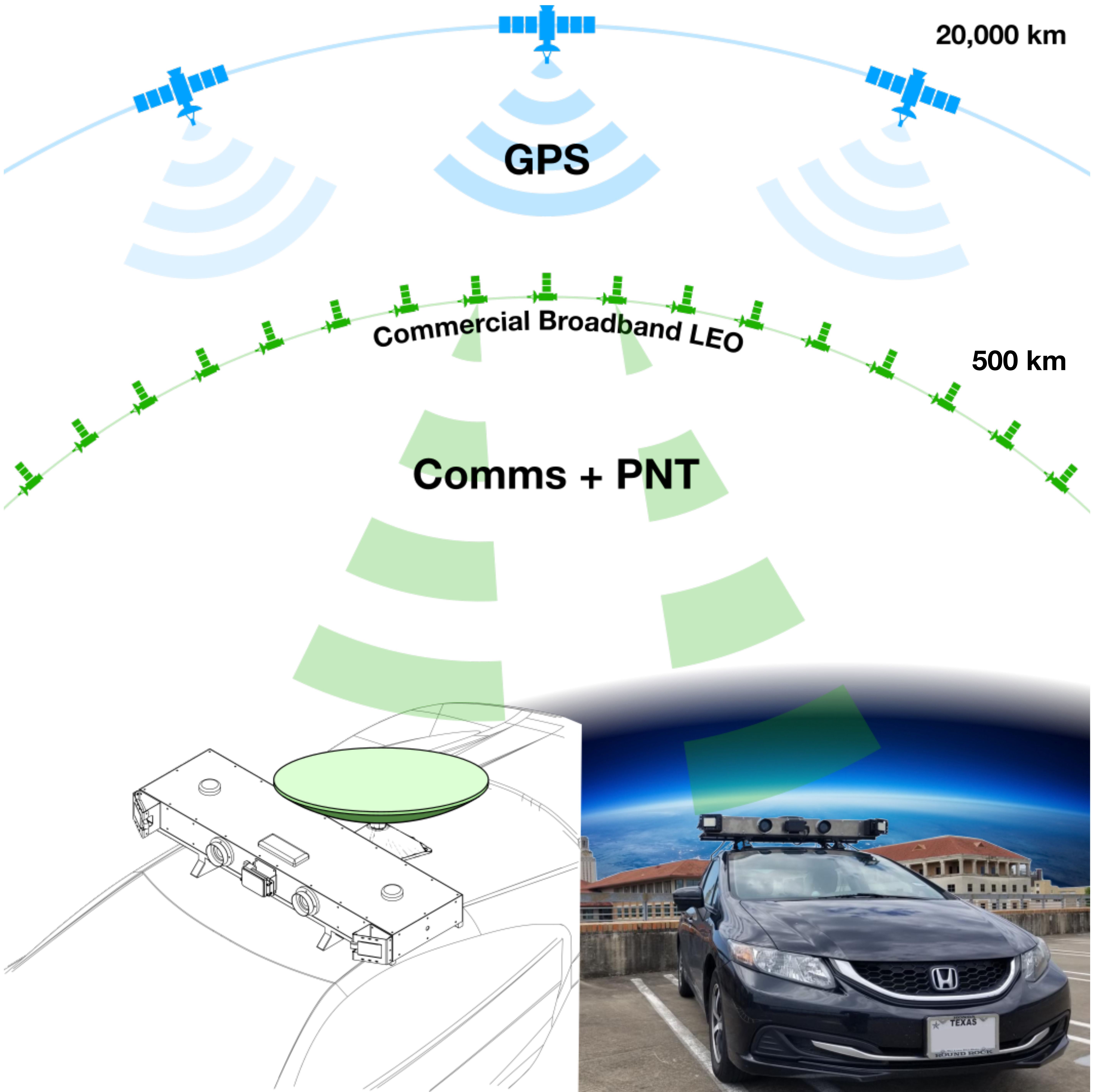
Traditional GNSS



~$100k

Mega-LEO


GPS
20,000 km
Mega-LEO
500 km


20,000 km
GPS
Commercial Broadband LEO
500 km
Comms + PNT
TEXAS

Goal

Mega-LEO PNT back-up to GPS

Starlink is live today…

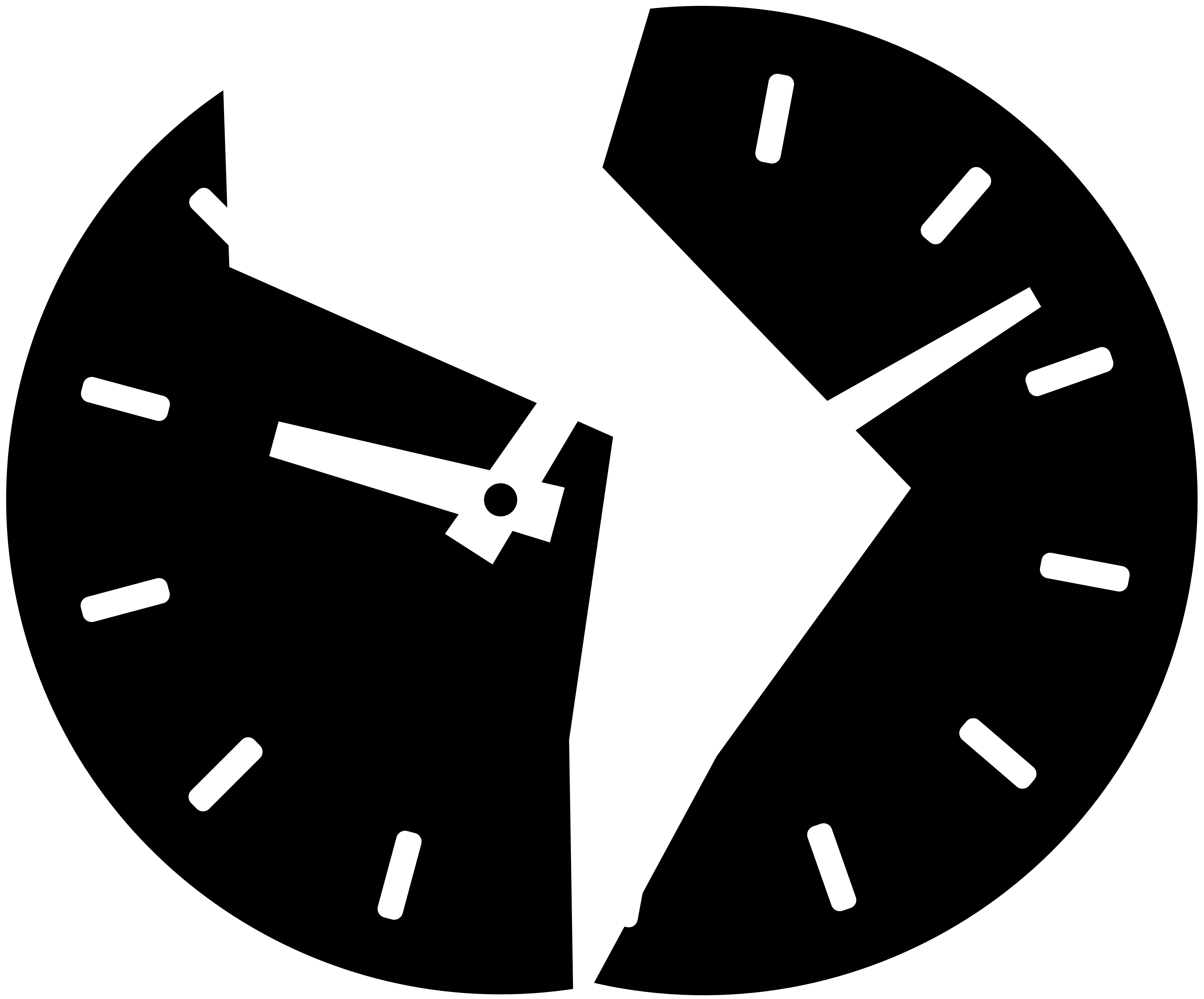
Suitable under fused LEO model?

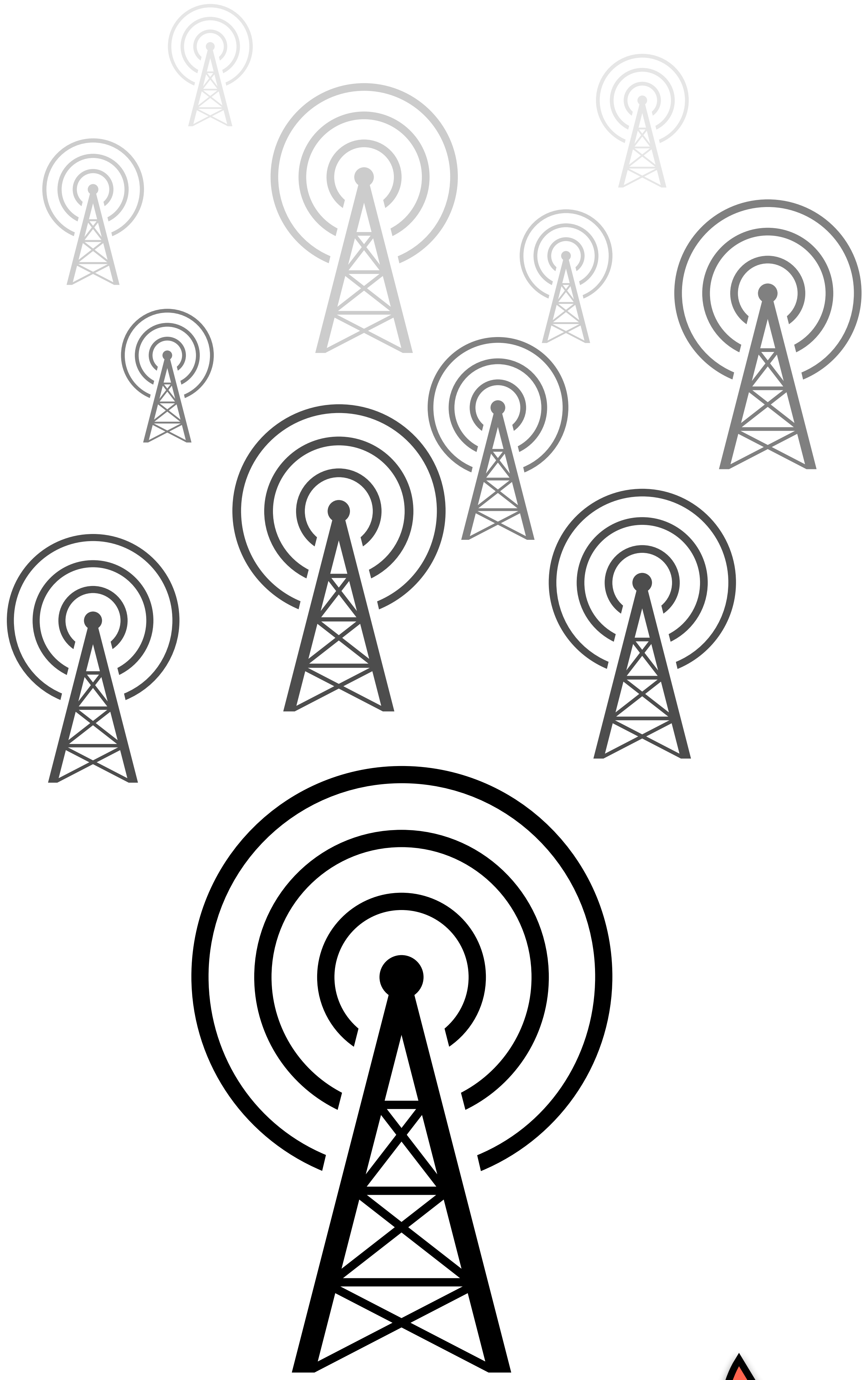
Risk

Signal timing may be unreliable!

Nobody wants to put up another reference network…

Signal timing may be unreliable!

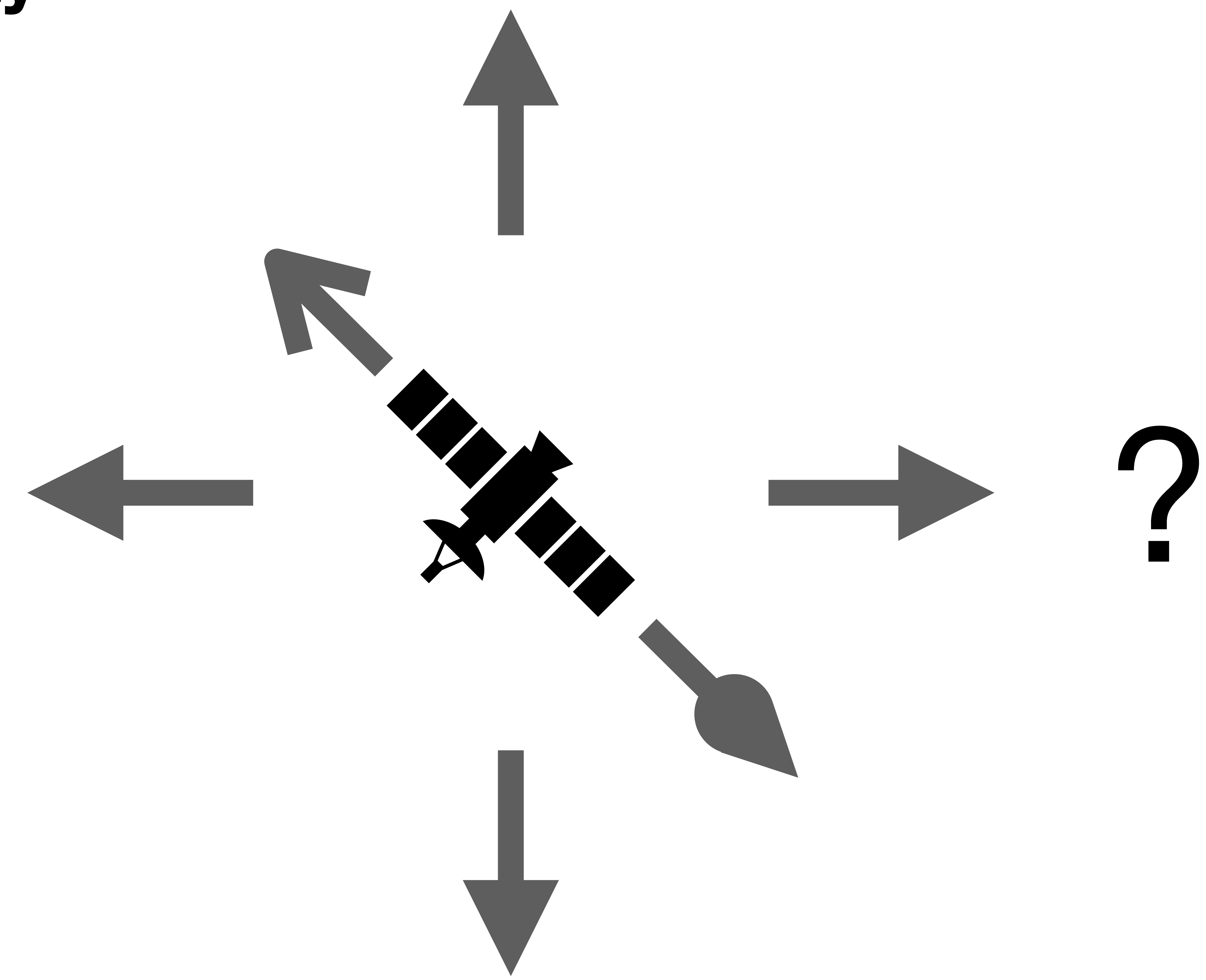




Nobody wants to put up another reference network...

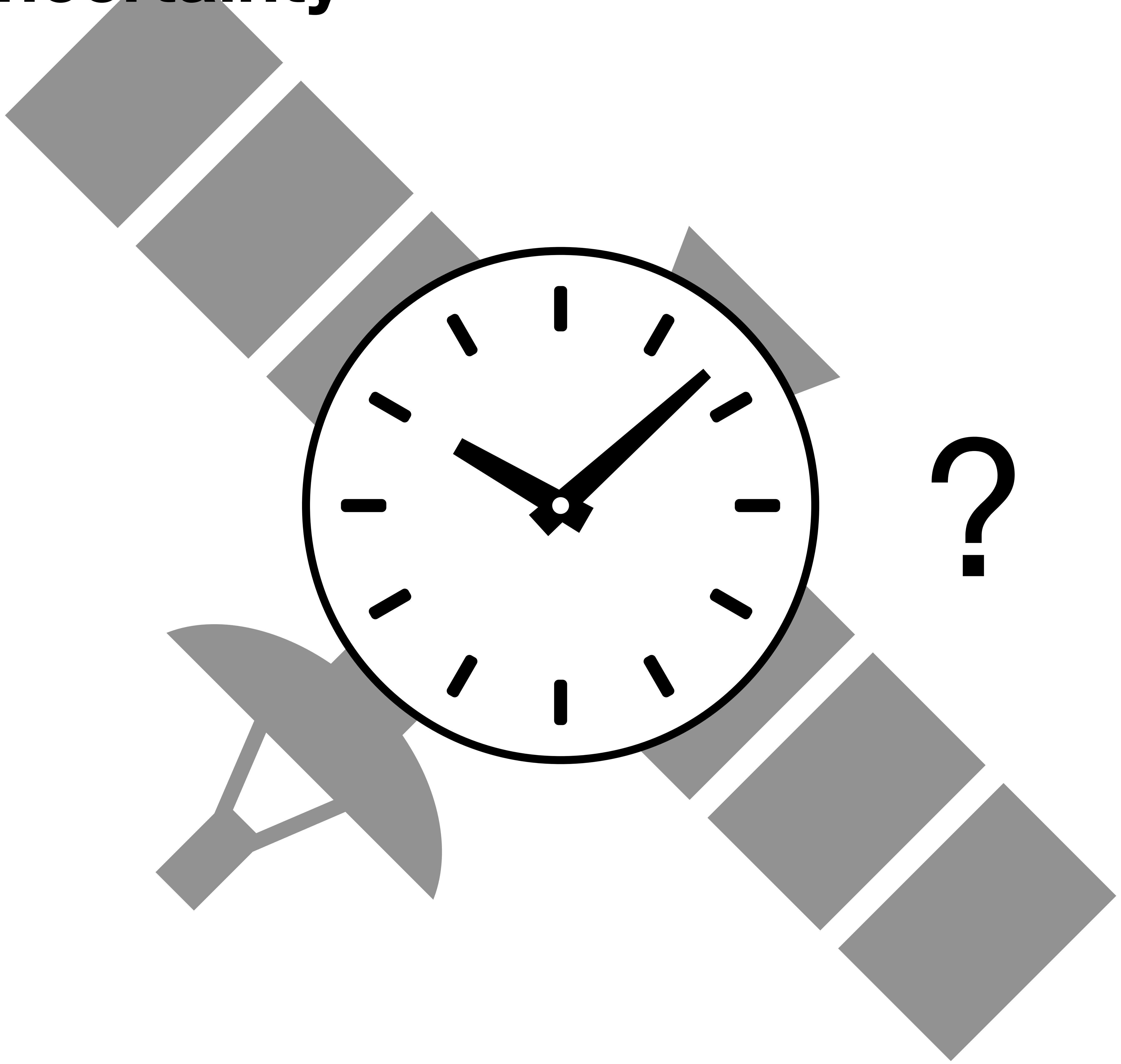
Sources of GNSS Error

Orbital Uncertainty



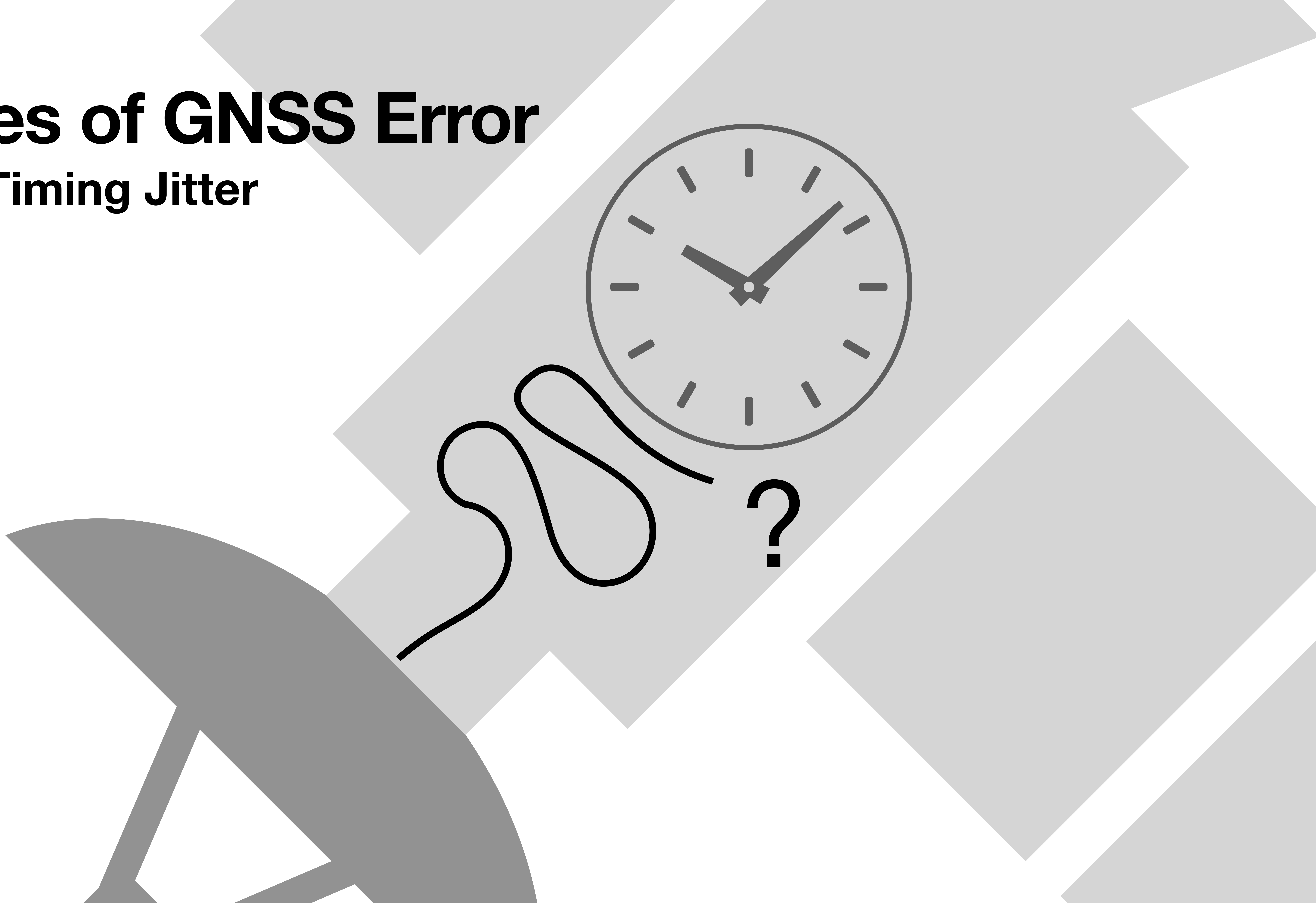
Sources of GNSS Error

Satellite Clock Uncertainty

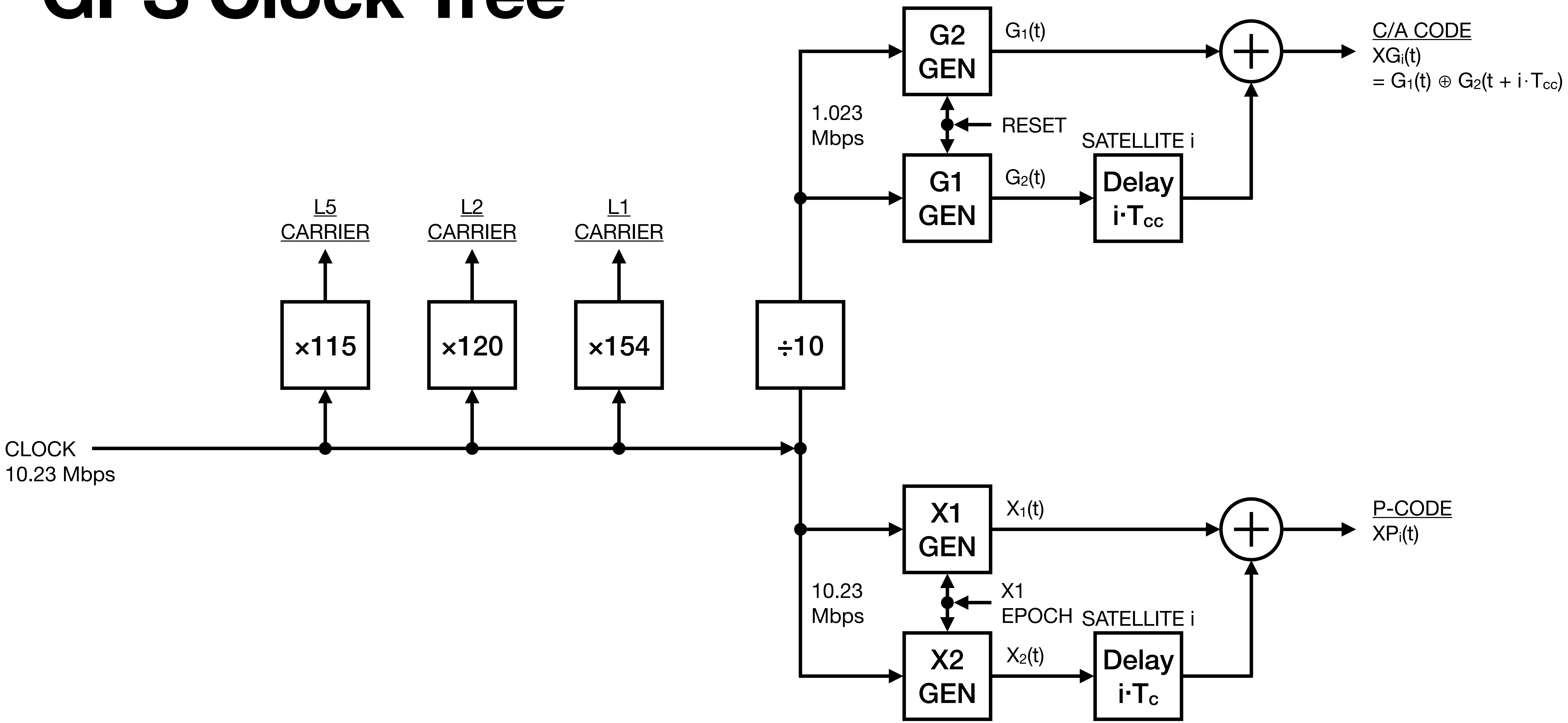


Sources of GNSS Error

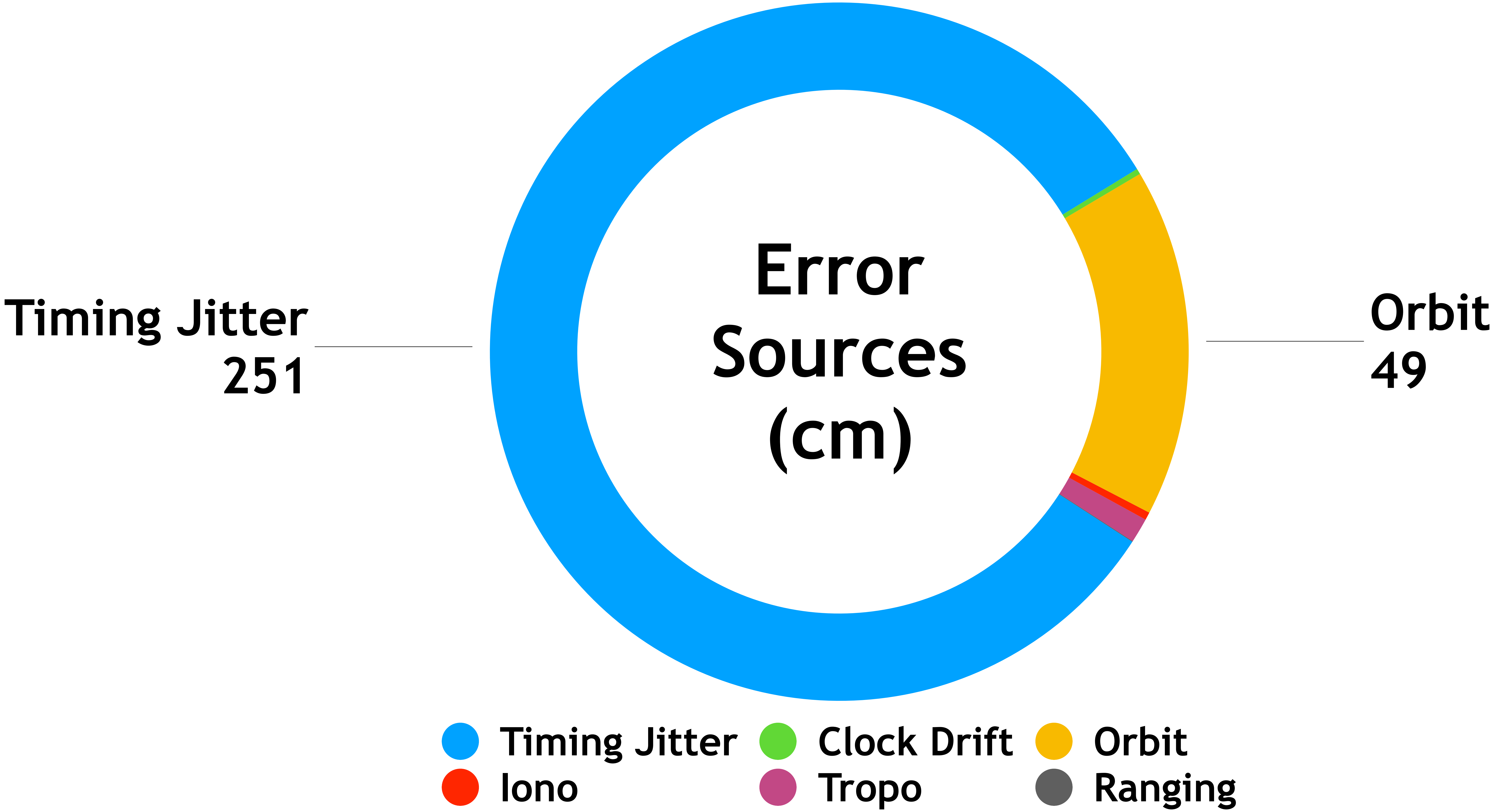
Satellite Timing Jitter



GPS Clock Tree



3.56m 95% RMS error, USA



Age-of-Ephemeris = 1s • Jitter = 1ns

$$\Pr\left\{ \|\Delta x\| > p_{95} \right\} \leq 5\%$$, where

$$p_{95} = k\sqrt{\mathrm{SISURE}^2 + \mathrm{Iono}^2 + \mathrm{Tropo}^2 + \mathrm{RNM}^2}$$

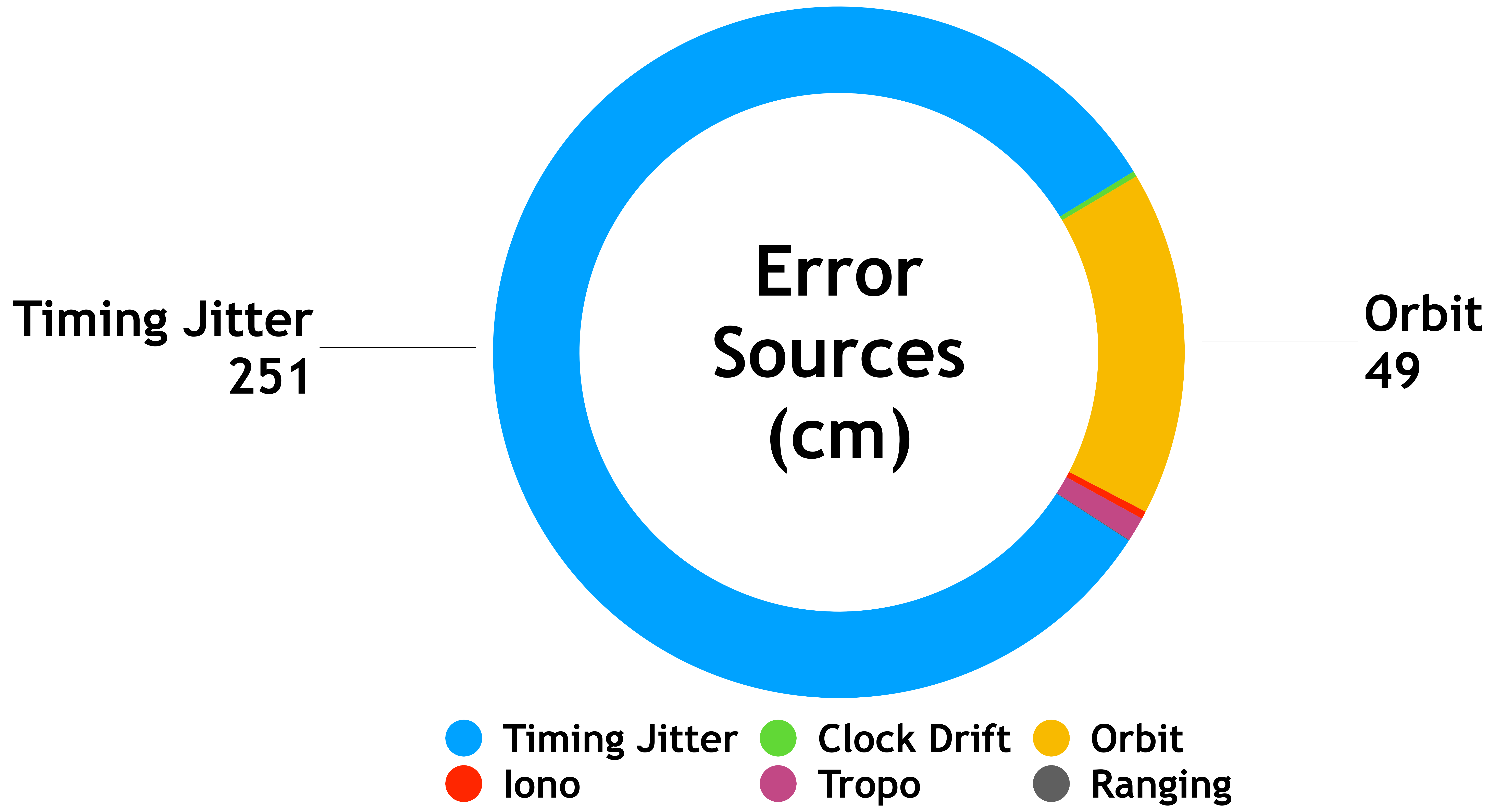
$$\mathrm{SISURE} = \left(w_R \cdot R + \sqrt{T^2 + \text{jitter}^2} \right)^2 + w_{AC}^2 \cdot (A^2 + C^2)$$

R, A, C = radial, along-track, cross-track error

$$k = \sqrt{\mathrm{CCDF}^{-1}_{\chi^2, k=3}(5\%)} \times \mathrm{PDOP}$$

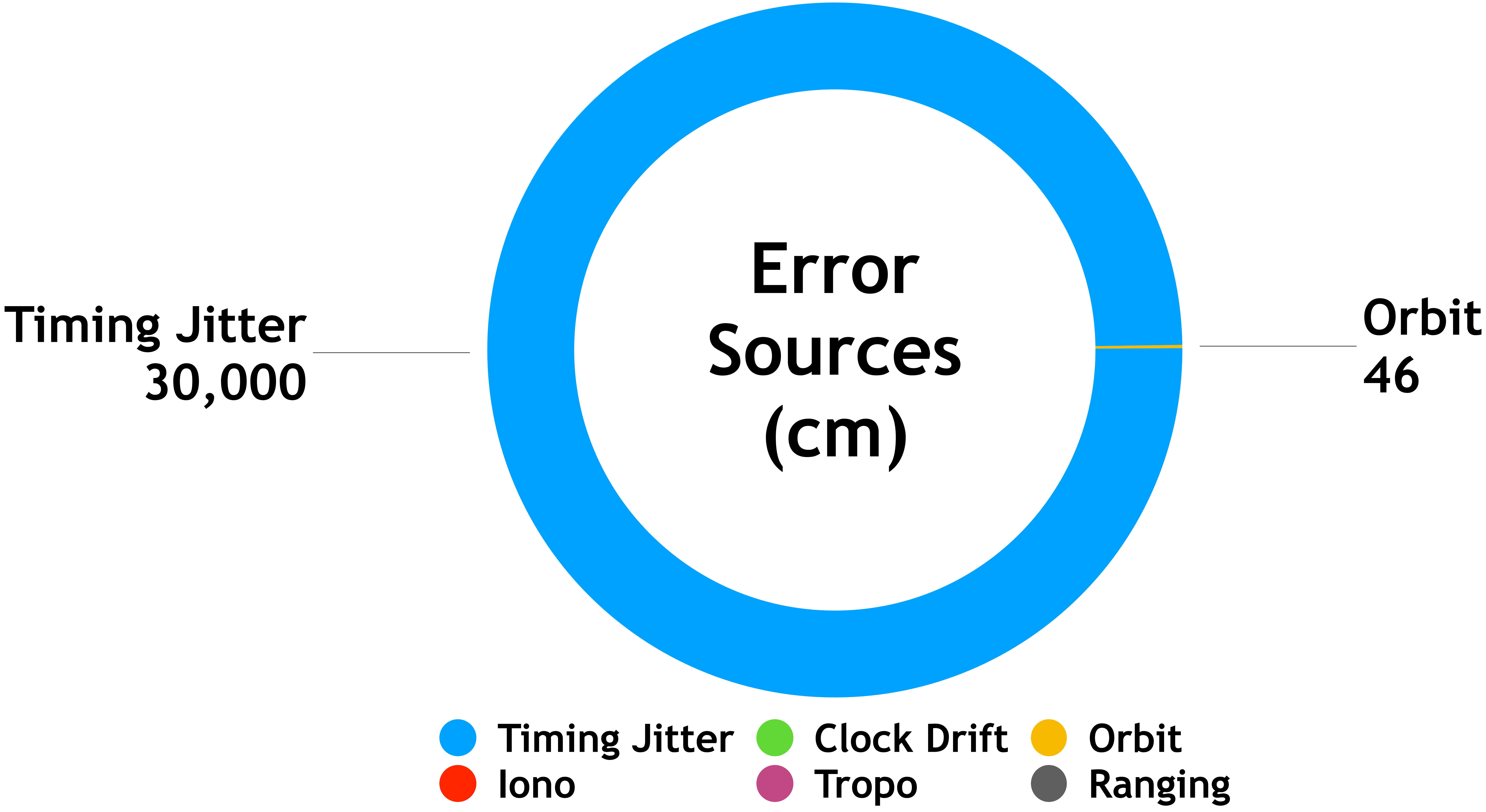
Timing Jitter, Clock Drift, Orbit
Iono, Tropo, Ranging

3.56m 95% RMS error, USA



Age-of-Ephemeris = 1s • Jitter = 1ns

301m 95% RMS error, USA



Age-of-Ephemeris = 1s • Jitter = 100ns

Path to goal?

Ephemeris via space-track.org (public)

Mechanically track one satellite

Record & reverse-engineer waveforms

Characterize timing predictability

On-line correlation + pseudorange tracking

Challenges in Signal Capture

Ku-band: not supported by SDRs • extreme line loss • components have long lead times

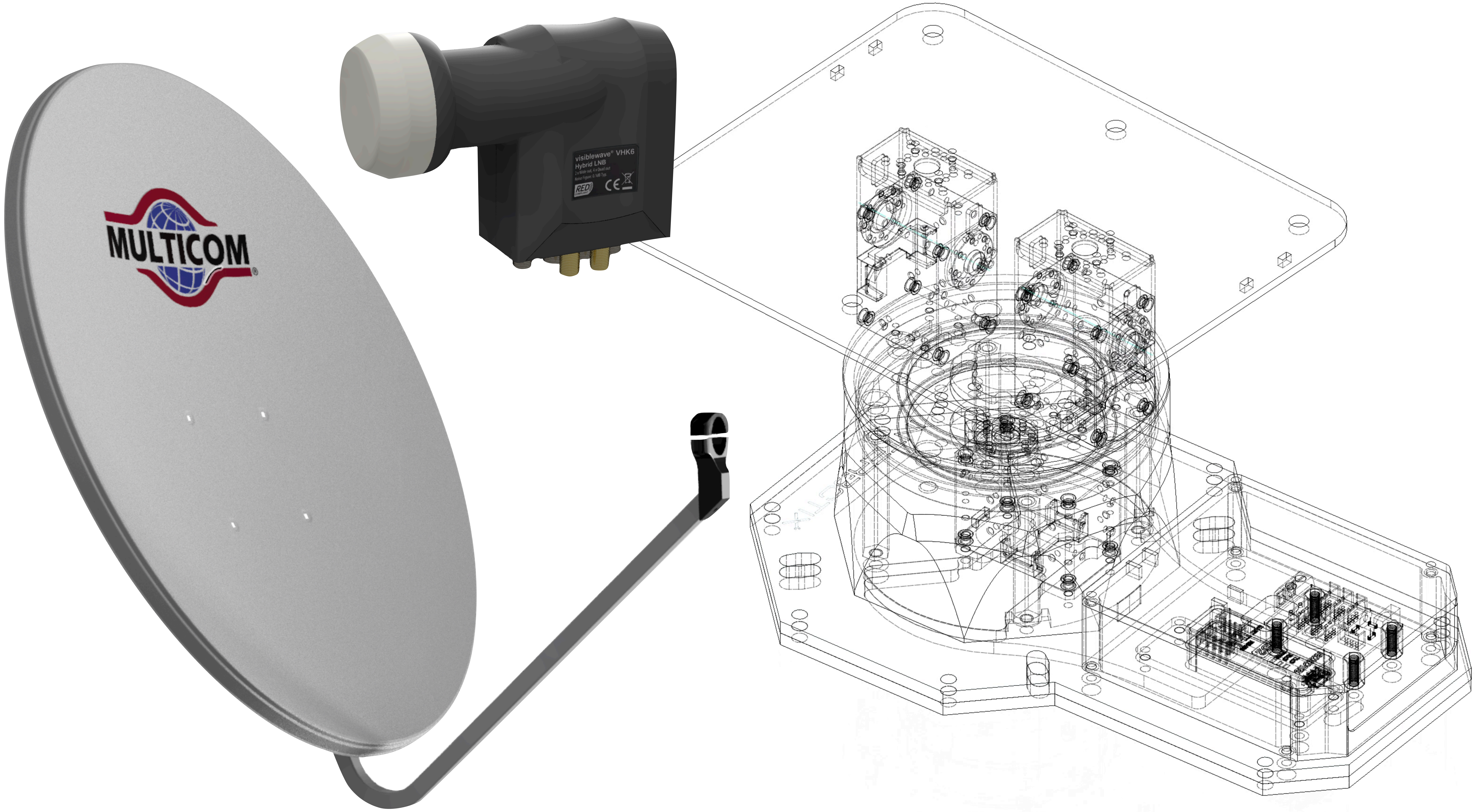
But! Block downconverters are ~$40 thanks to the EU satellite TV market

3 cm wavelength ⇒ antennas w/ adequate A_{eff} <u>highly</u> directional

Commercial, off-the-shelf 75cm offset parabolic dish

Antenna tracking needed to within ~1°

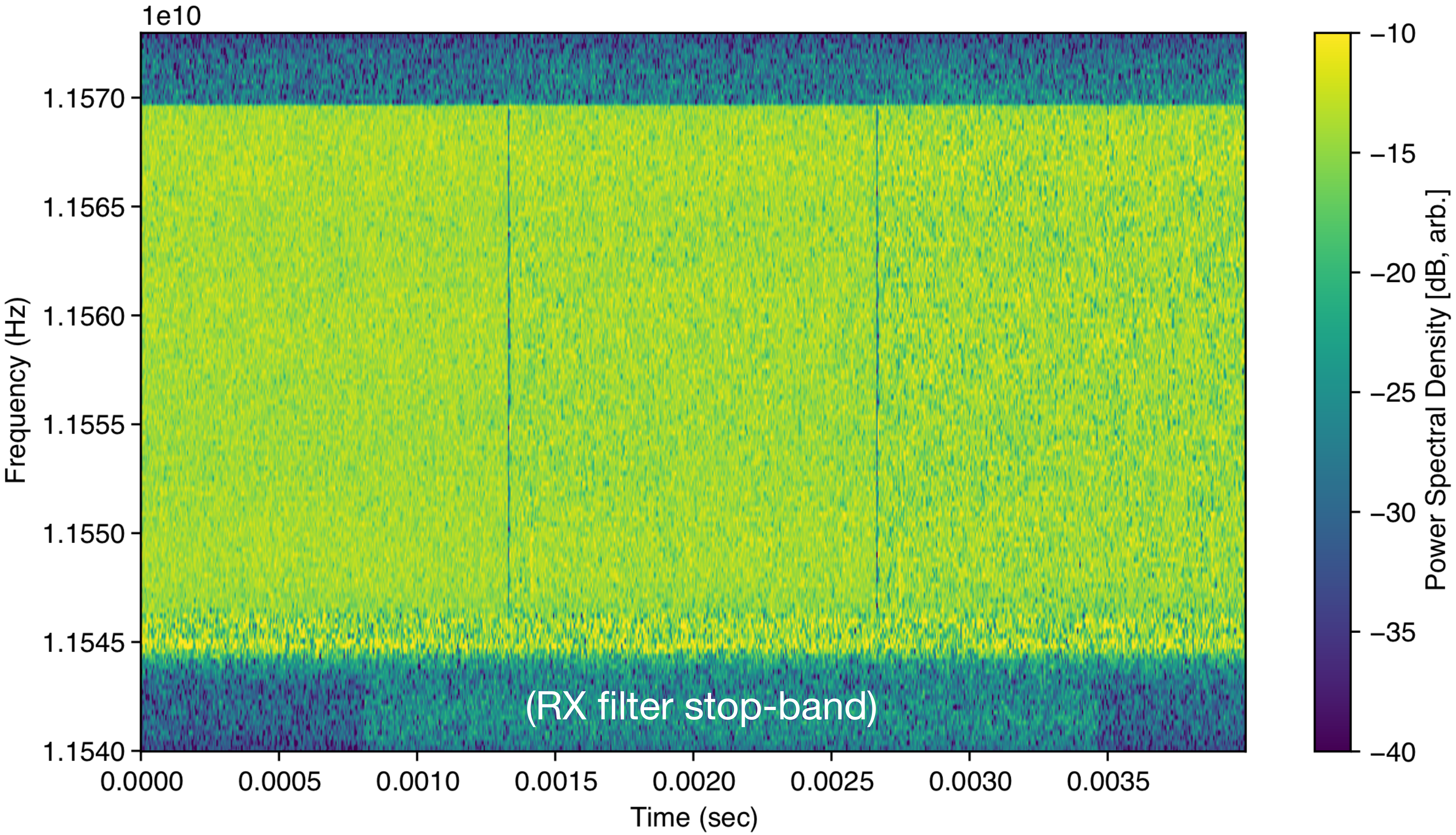
Each satellite's downlink active time ≤ 150 sec


MULTICOM
visiblewave® VHK6
Hybrid LNB

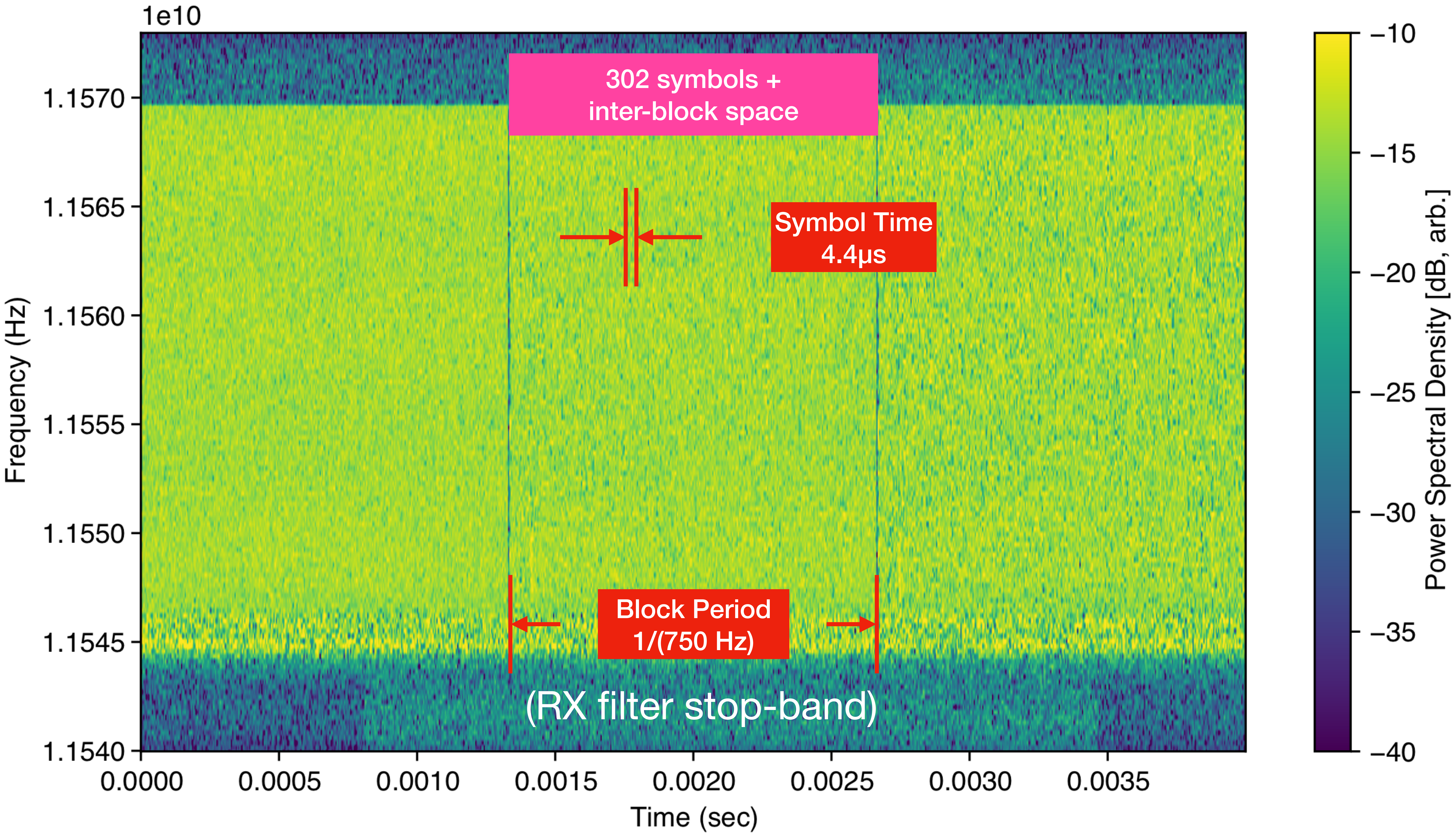

Rafael
Micro
RT361S
G3PM6912
MD61A-1B
2018.07.12
J25.024L20S8
221
6R8
SS24
3R3

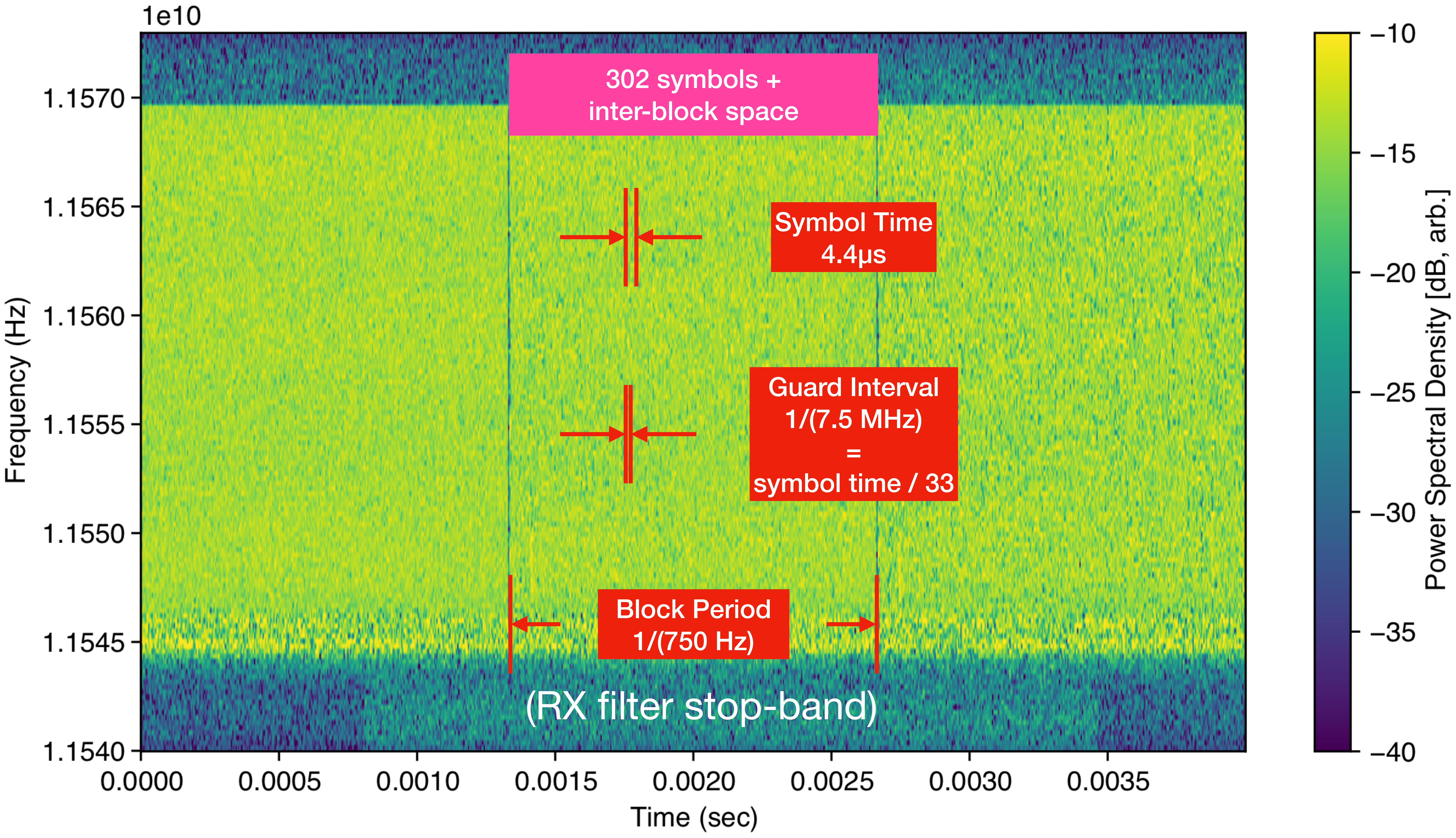

MULTICOM
Satellite
00%
ON
Receiver
SF-95DR
ATT
ATT
Compass
Light
Buzzer
NATIONAL INSTRUMENTS
STARTUP: [1] RAID, [2] CHASSIS, [3] PC

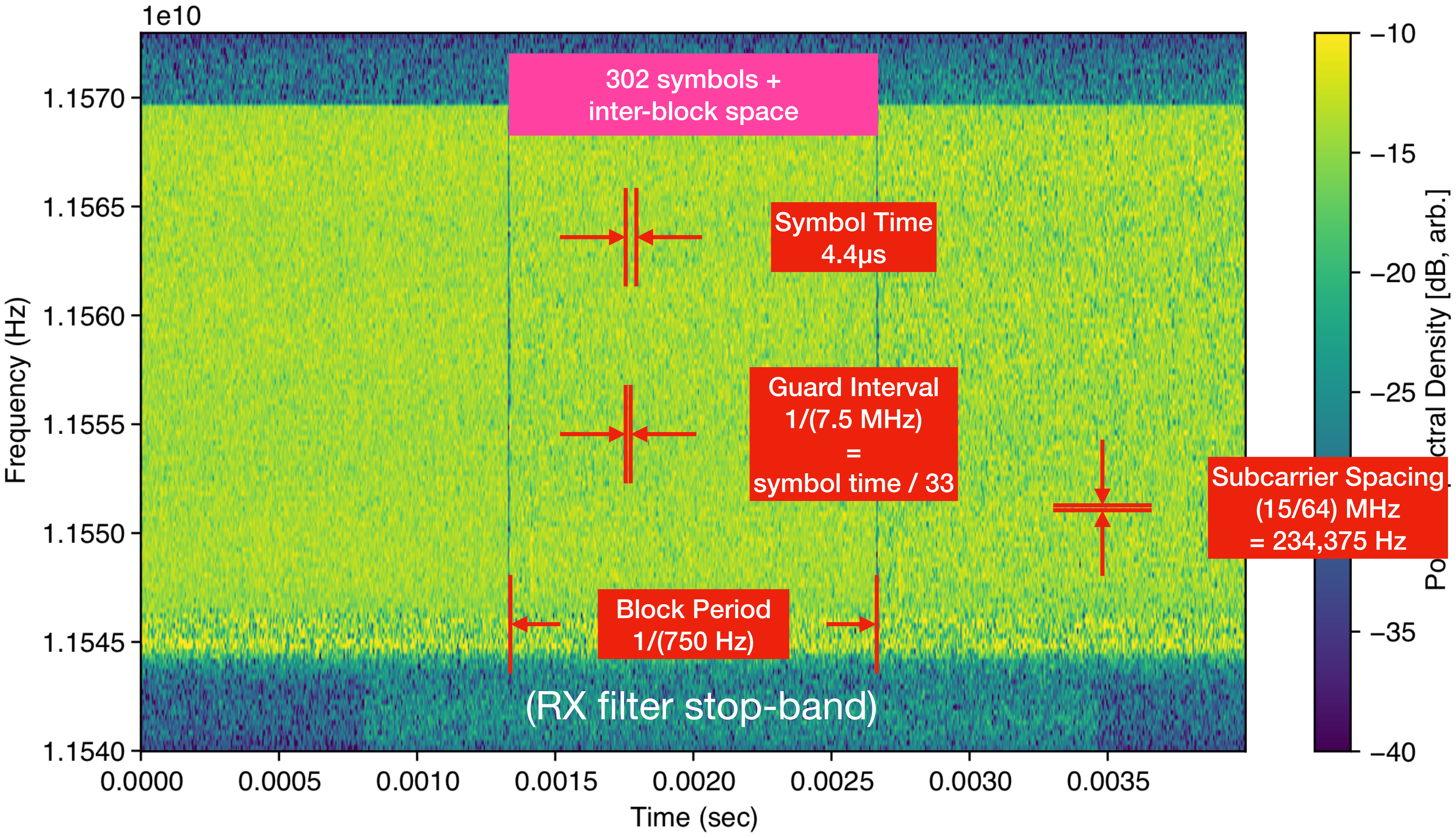
ID	Lat	Lon	Alt	Az	El
1568	+26.7269	-79.0312	543.9	+97.6	+7.1
1893	+29.8513	-111.5872	547.3	+271.4	+15.4
1913	+36.7835	-100.1665	545.6	+343.3	+31.3
1918	+35.1210	-72.9135	545.4	+70.5	+1.6
1985	+52.7070	-110.4289	353.1	+341.0	-5.0
2009	+24.8263	-105.9197	543.9	+235.1	+22.7
2011	+47.3228	-81.8948	549.4	+31.3	+2.1
2012	+51.4638	-101.1708	353.4	+354.1	-2.5
2015	+52.5963	-109.3271	354.7	+342.4	-4.6
2019	+51.6437	-102.2252	352.4	+352.4	-2.8
2022	+44.8146	-98.1729	550.2	+358.8	+10.8
2060	+52.2409	-106.2296	353.7	+346.5	-3.8
2153	+49.1160	-120.9470	548.2	+323.5	-2.6
2301	+12.2076	-114.5943	468.3	+224.6	-2.4
2349	+22.3660	-124.1023	544.9	+257.8	-1.9
2560	+39.9994	-75.0490	547.1	+56.2	+2.2
1074	+16.5752	-84.0217	546.2	+134.4	+4.8
1088	+44.4027	-118.2650	546.9	+316.7	+1.5
1143	+48.4487	-93.6025	547.7	+8.7	+5.1
1156	+8.6454	-97.6994	544.1	+179.9	+1.3
1162	+38.4145	-127.5393	547.2	+296.4	-2.7
1209	+49.1616	-71.0807	549.4	+39.4	-4.3
1211	+52.9816	-87.4790	552.4	+15.4	-0.8
1228	+53.1970	-102.5672	549.0	+352.6	-0.2
1329	+30.3783	-65.1631	546.0	+81.4	-4.7
1337	+46.1188	-70.0985	547.8	+45.9	-3.5
1442	+43.4511	-86.0458	549.2	+32.1	+8.2
1443	+30.3727	-105.1624	544.8	+272.6	+33.0
1448	+15.1955	-119.4409	544.6	+237.8	-2.0
1545	+35.0878	-112.8542	546.3	+294.5	+12.2
1559	+11.1957	-92.6473	545.1	+164.9	+3.5
1630	+27.9920	-84.5886	546.1	+98.0	+16.0
1637	+28.0017	-124.5946	544.3	+271.2	-0.6



1e10
1.1570
1.1565
1.1560
1.1555
1.1550
1.1545
1.1540
Frequency (Hz)
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
Time (sec)
(RX filter stop-band)
−10
−15
−20
−25
−30
−35
−40
Power Spectral Density [dB, arb.]


1e10
1.1570
1.1565
1.1560
1.1555
1.1550
1.1545
1.1540
Frequency (Hz)
302 symbols +
inter-block space
Symbol Time
4.4μs
Block Period
1/(750 Hz)
(RX filter stop-band)
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
Time (sec)
−10
−15
−20
−25
−30
−35
−40
Power Spectral Density [dB, arb.]


1e10
1.1570
1.1565
1.1560
1.1555
1.1550
1.1545
1.1540
Frequency (Hz)
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
Time (sec)
302 symbols + inter-block space
Symbol Time 4.4μs
Guard Interval 1/(7.5 MHz) = symbol time / 33
Block Period 1/(750 Hz)
(RX filter stop-band)
−10
−15
−20
−25
−30
−35
−40
Power Spectral Density [dB, arb.]

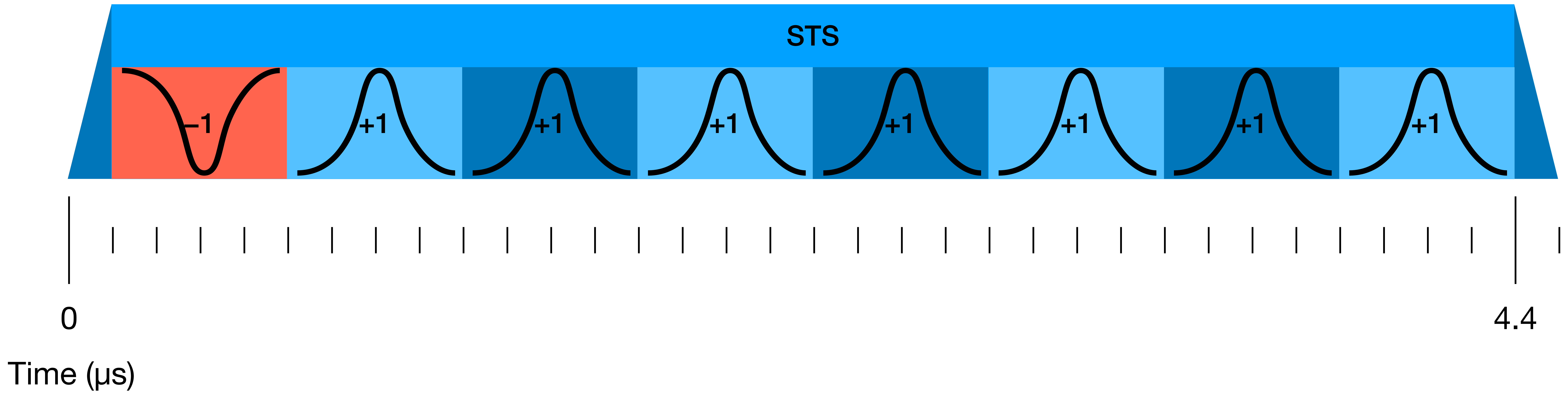

1e10
302 symbols +
inter-block space
Symbol Time
4.4µs
Guard Interval
1/(7.5 MHz)
=
symbol time / 33
Subcarrier Spacing
(15/64) MHz
= 234,375 Hz
Block Period
1/(750 Hz)
(RX filter stop-band)
Frequency (Hz)
Time (sec)
1.1570
1.1565
1.1560
1.1555
1.1550
1.1545
1.1540
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
−10
−15
−20
−25
−35
−40
Po
ctral Density [dB, arb.]

Signal Structure: Time Domain

Block

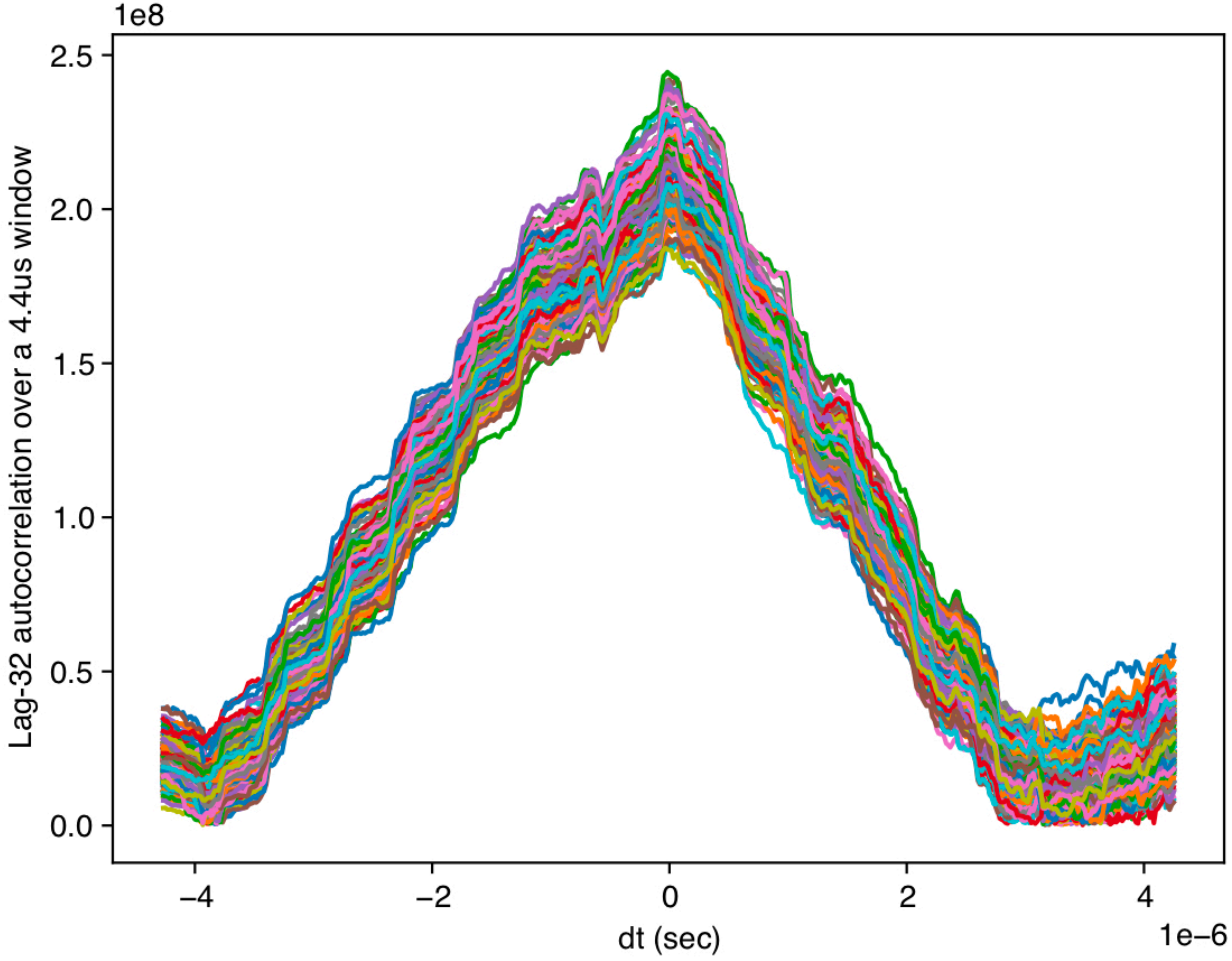
Signal Structure: Time Domain

Short Training Sequences

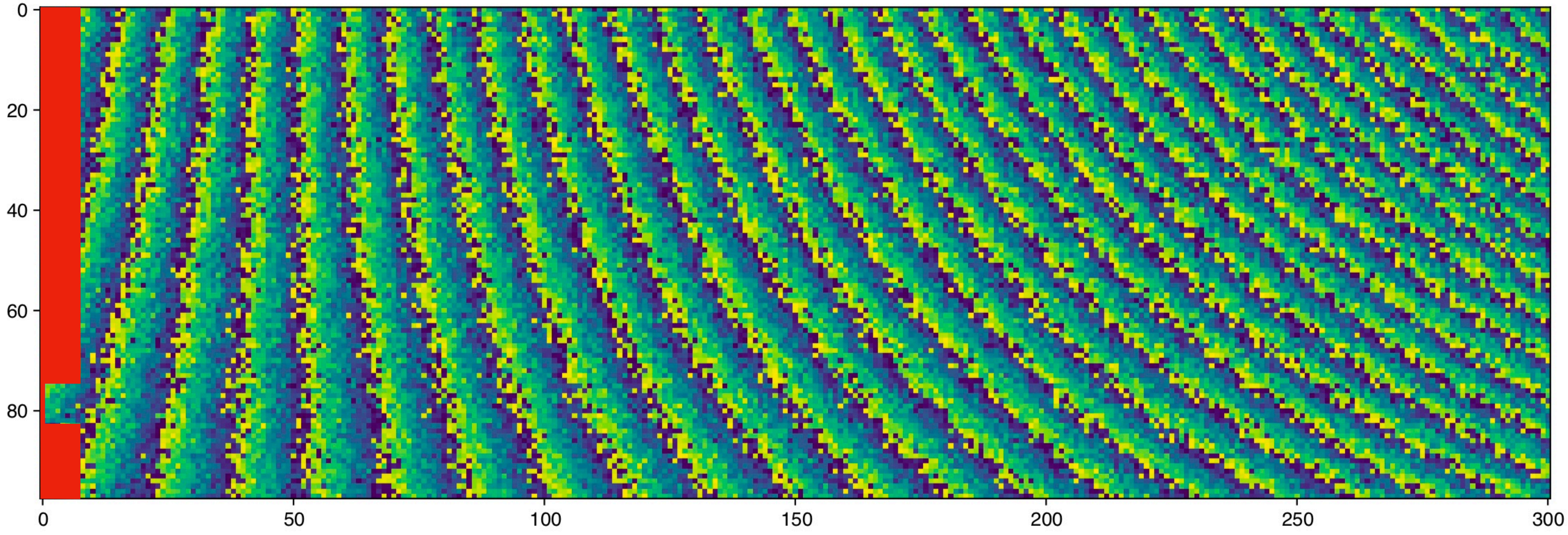


Signal Structure: Time Domain

Code-Phase from STS Correlation



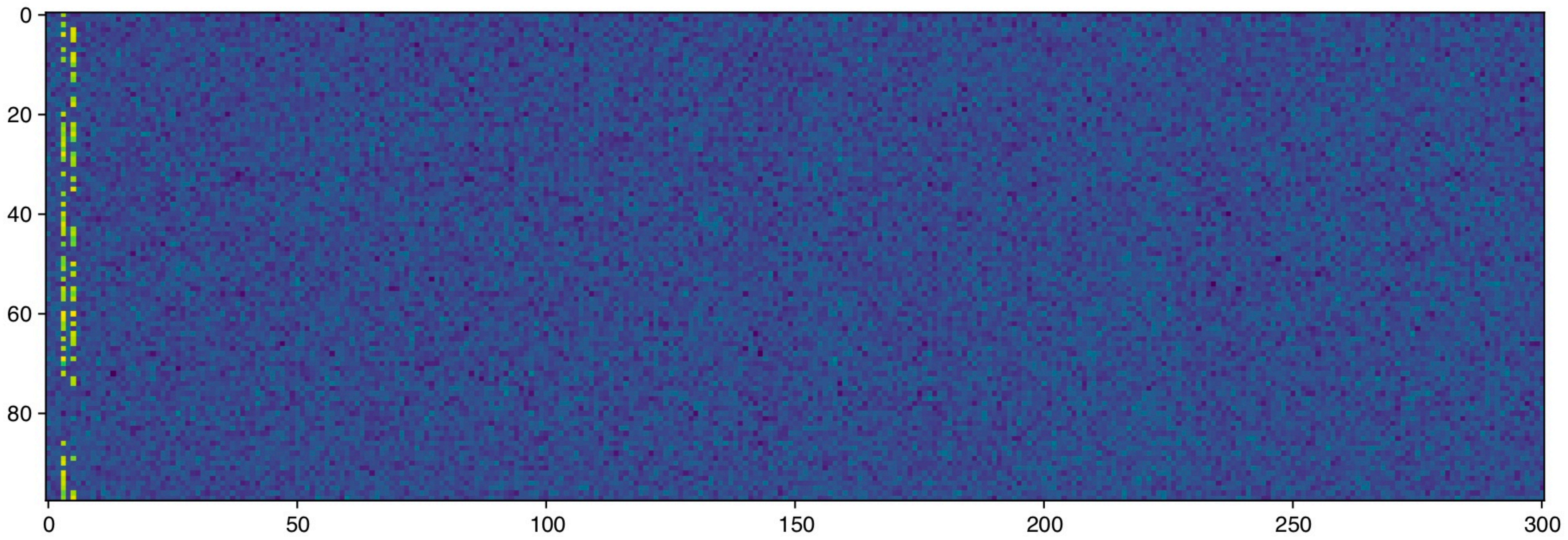
Signal Structure: Frequency Domain

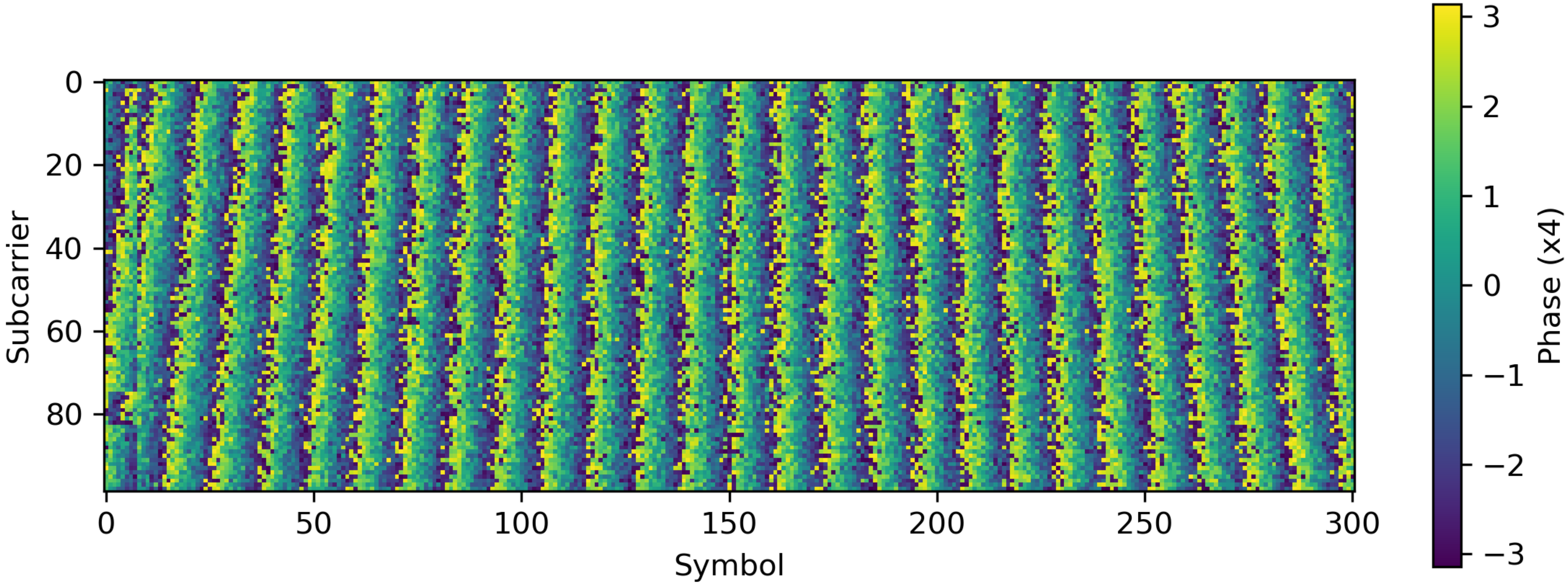


What about phase stability?
intra-block, inter-block

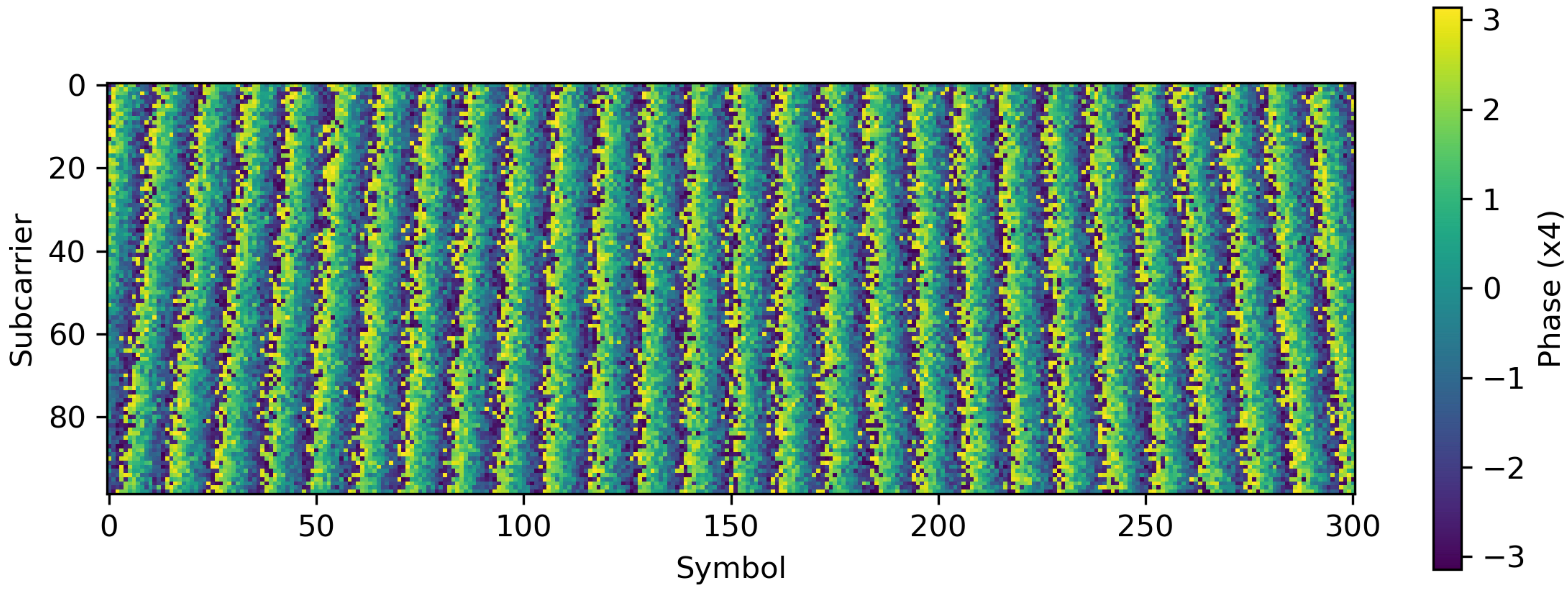
Quadratic phase + phase noise (tough to separate RX from TX noise)

Beautifully clean, traceable clock carrier doesn't happen by accident…
BUT! Within an OFDM packet, phase must be ultra-stable or comms won't work!
Short timescales: OFDM will tell you it's definitely good
Longer timescales (i.e. between packets): big risk that modem takes arbitrary breaks/doesn't run its NCO

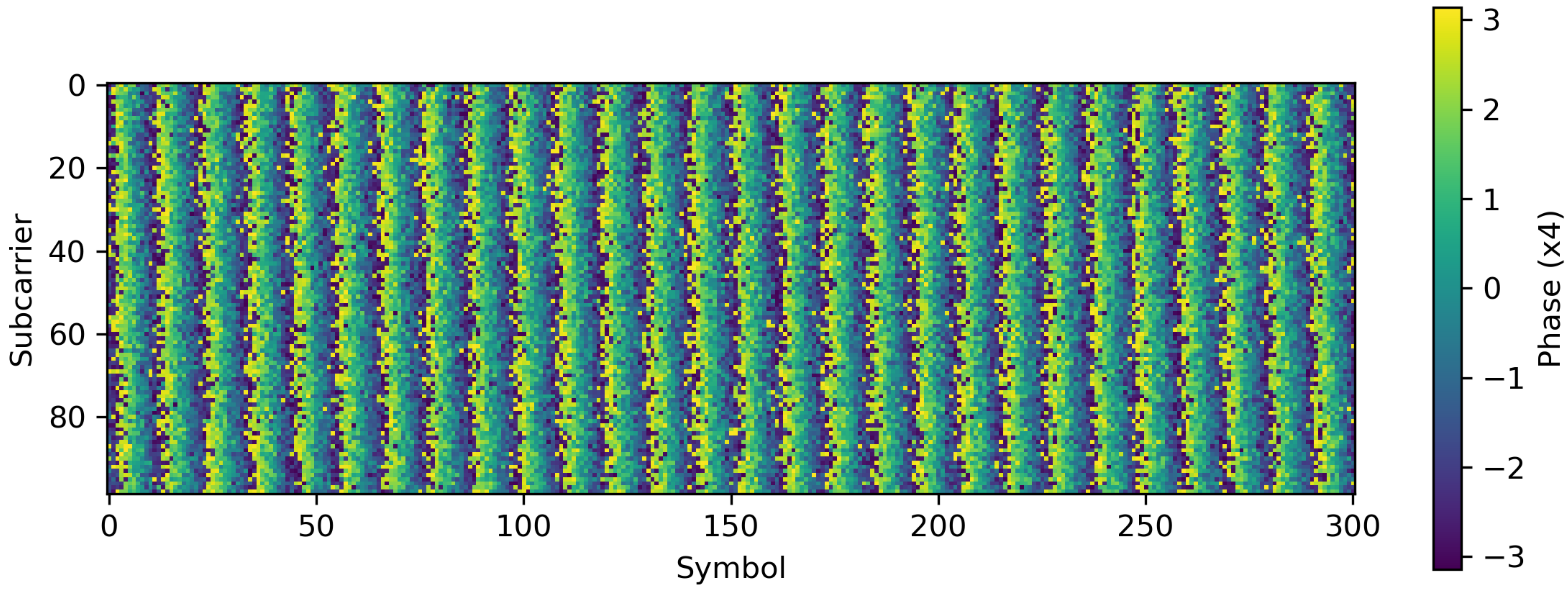




0
20
40
60
80
Subcarrier
0
50
100
150
200
250
300
Symbol
3
2
1
0
−1
−2
−3
Phase (x4)



Subcarrier
0
20
40
60
80
0
50
100
150
200
250
300
Symbol
Phase (x4)
3
2
1
0
−1
−2
−3



0
20
40
60
80
Subcarrier
0
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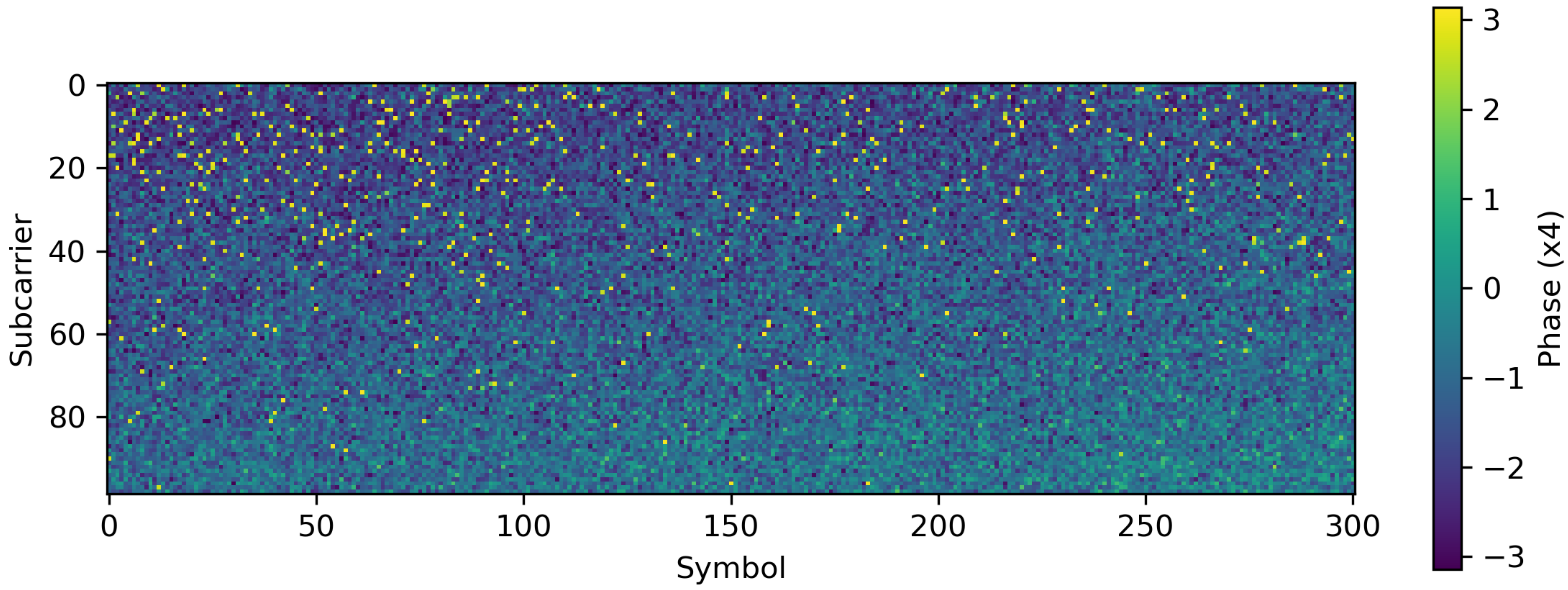
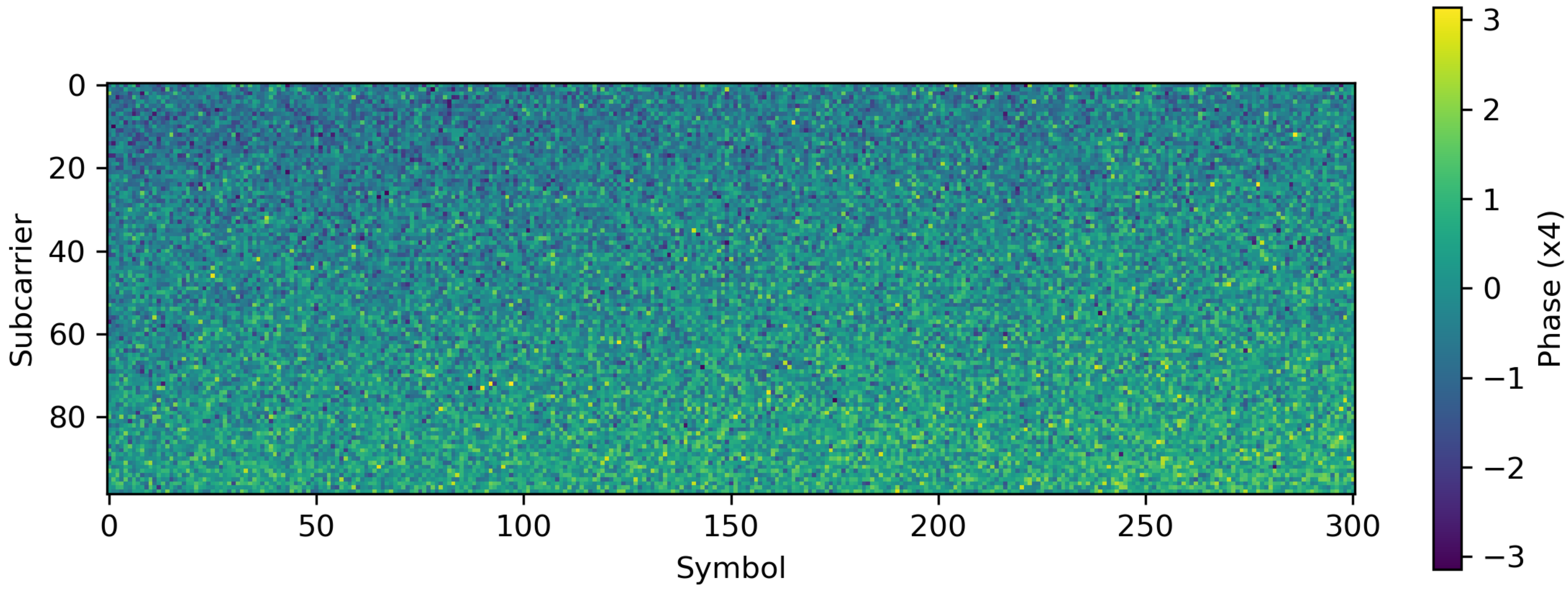
100
150
200
250
300
Symbol
3
2
1
0
−1
−2
−3
Phase (x4)



Subcarrier
0
20
40
60
80
Symbol
0
50
100
150
200
250
300
Phase (x4)
3
2
1
0
−1
−2
−3



0
20
40
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Subcarrier
0
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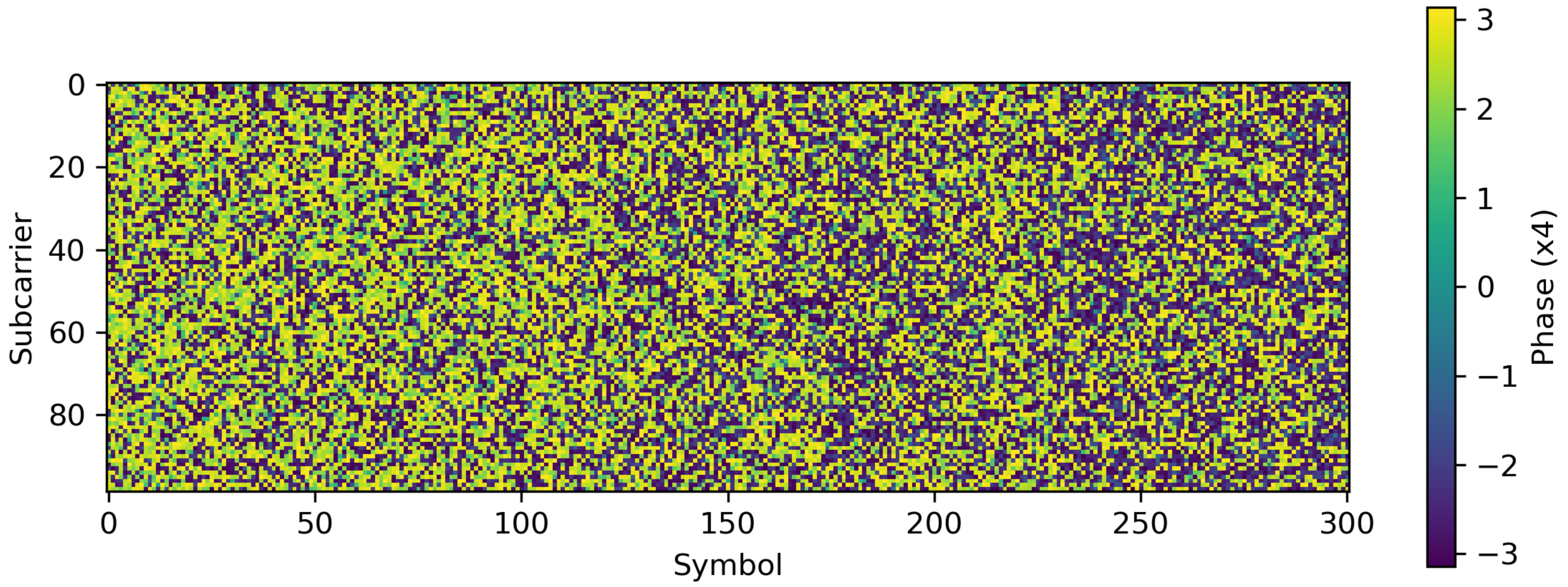
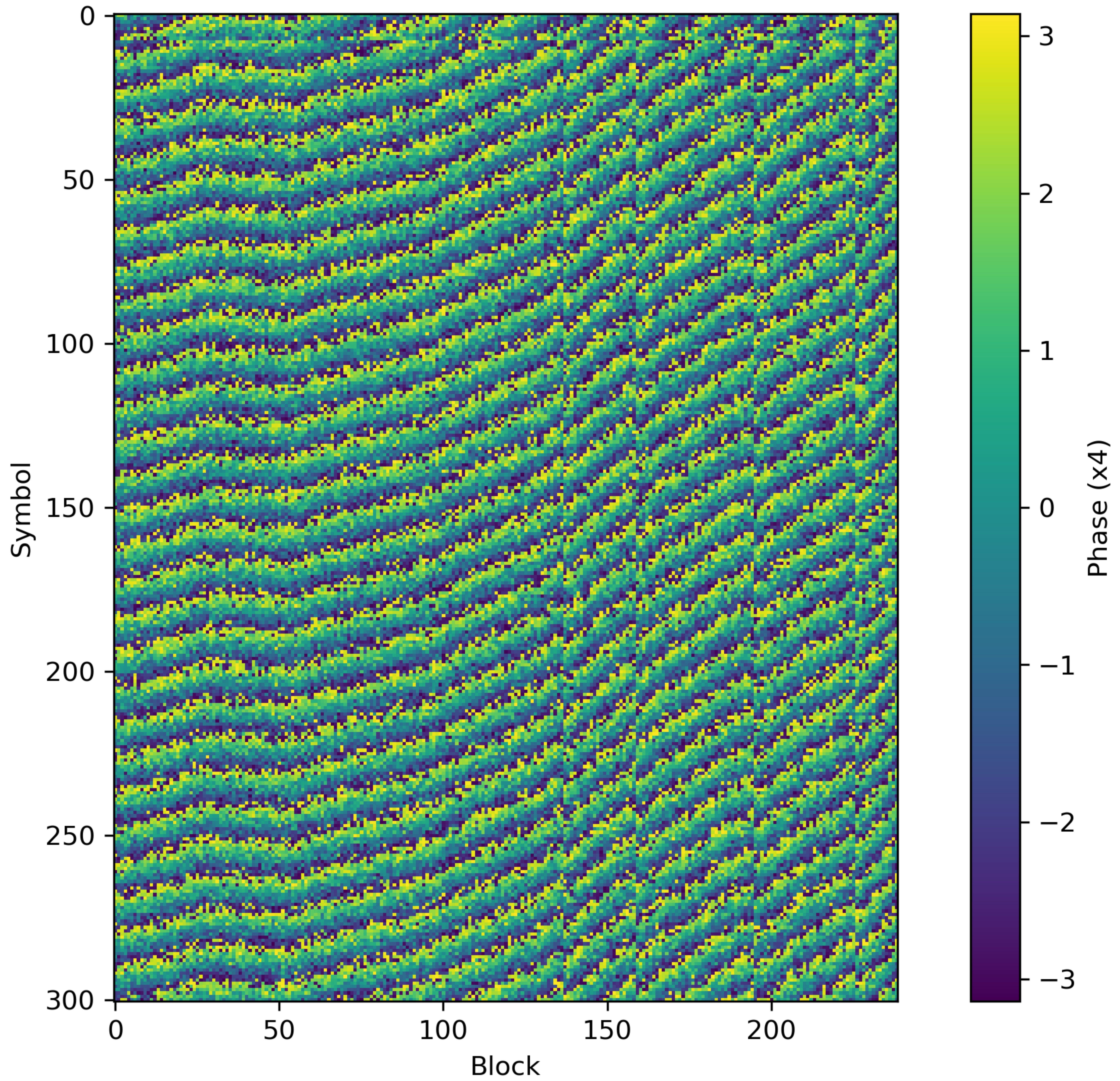
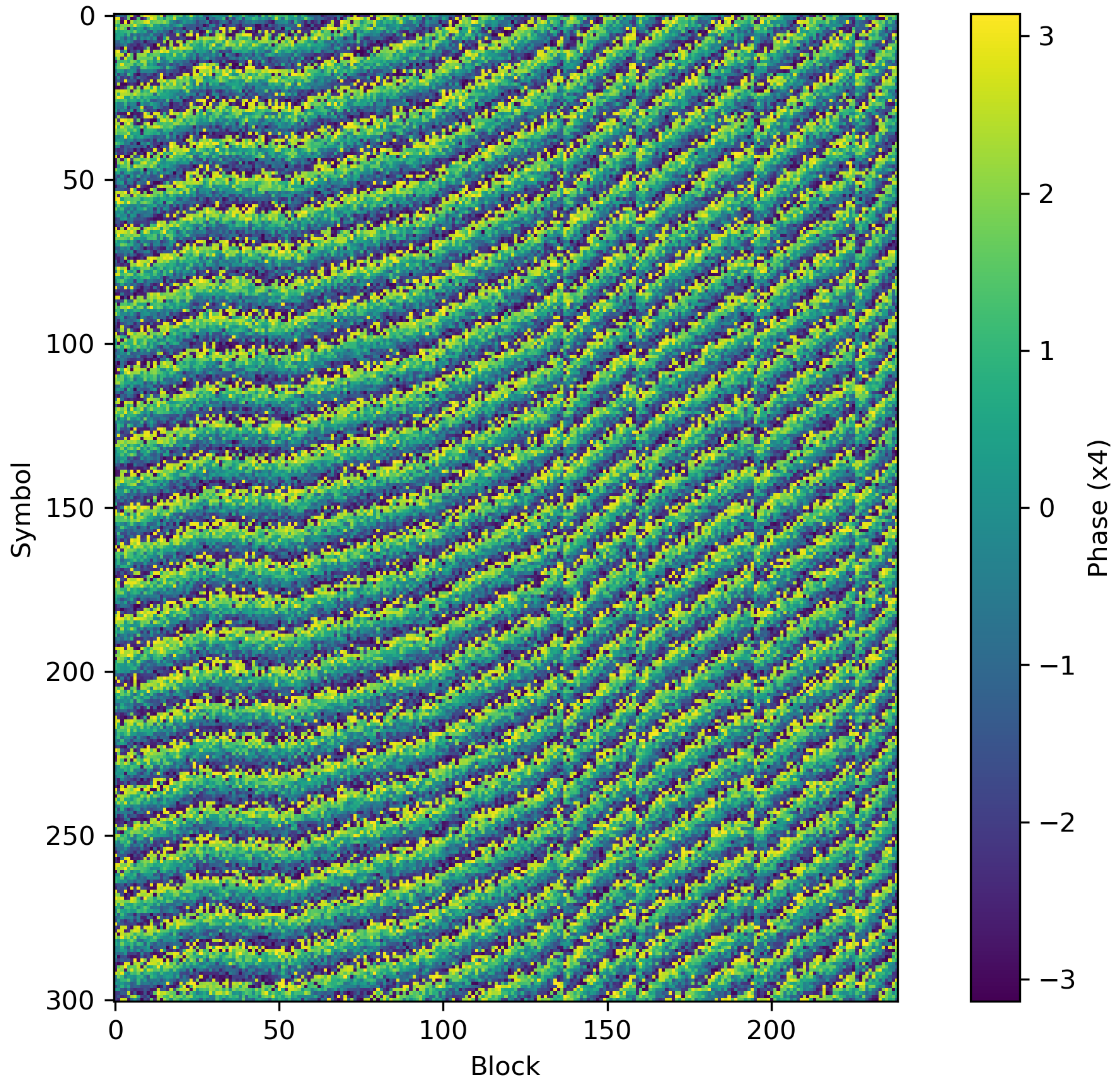
100
150
200
250
300
Symbol
3
2
1
0
−1
−2
−3
Phase (x4)



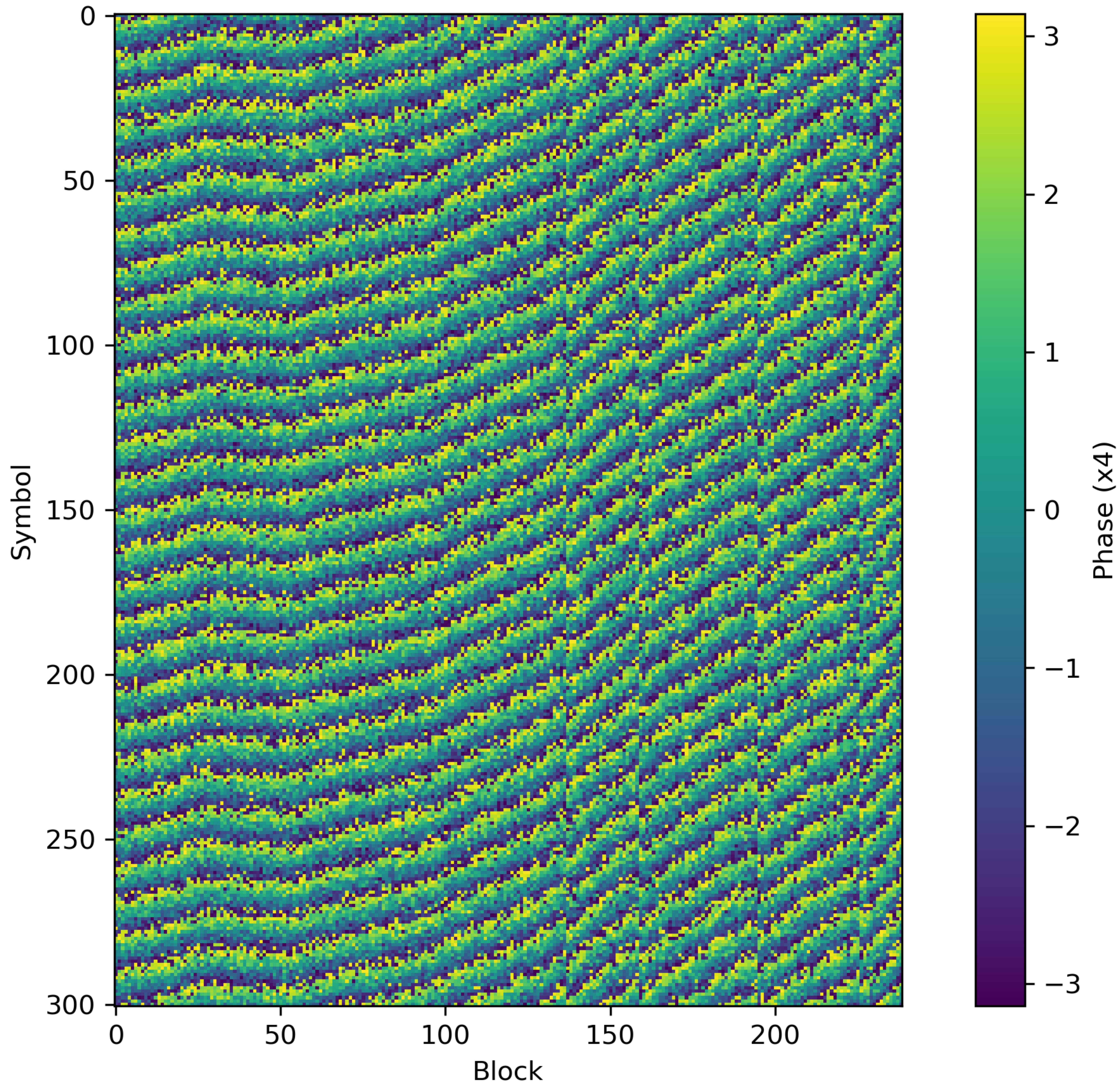
Subcarrier
0
20
40
60
80
Symbol
0
50
100
150
200
250
300
Phase (x4)
3
2
1
0
−1
−2
−3



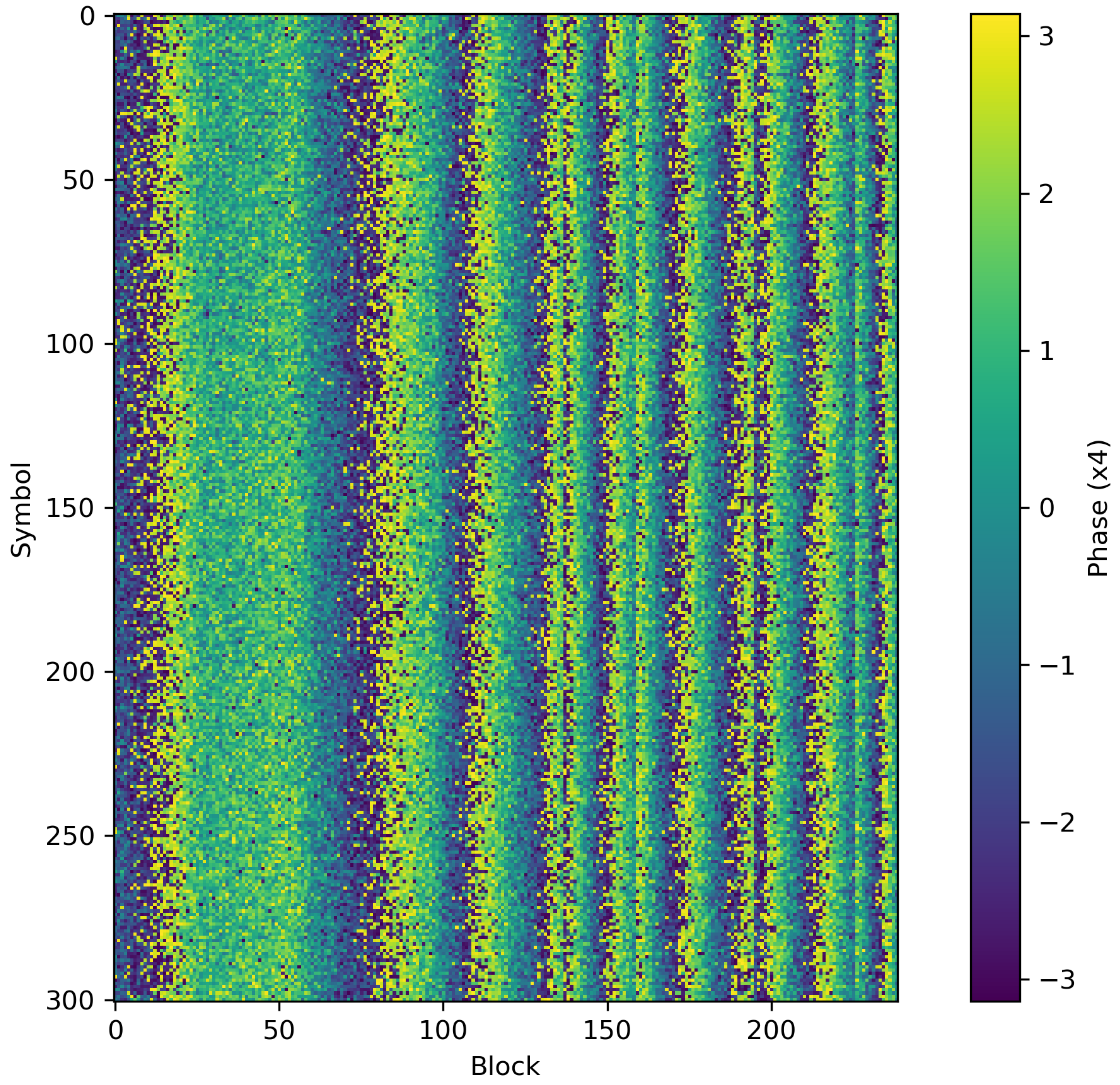
Symbol
Block
Phase (x4)
0
50
100
150
200
250
300
0
50
100
150
200
3
2
1
0
−1
−2
−3



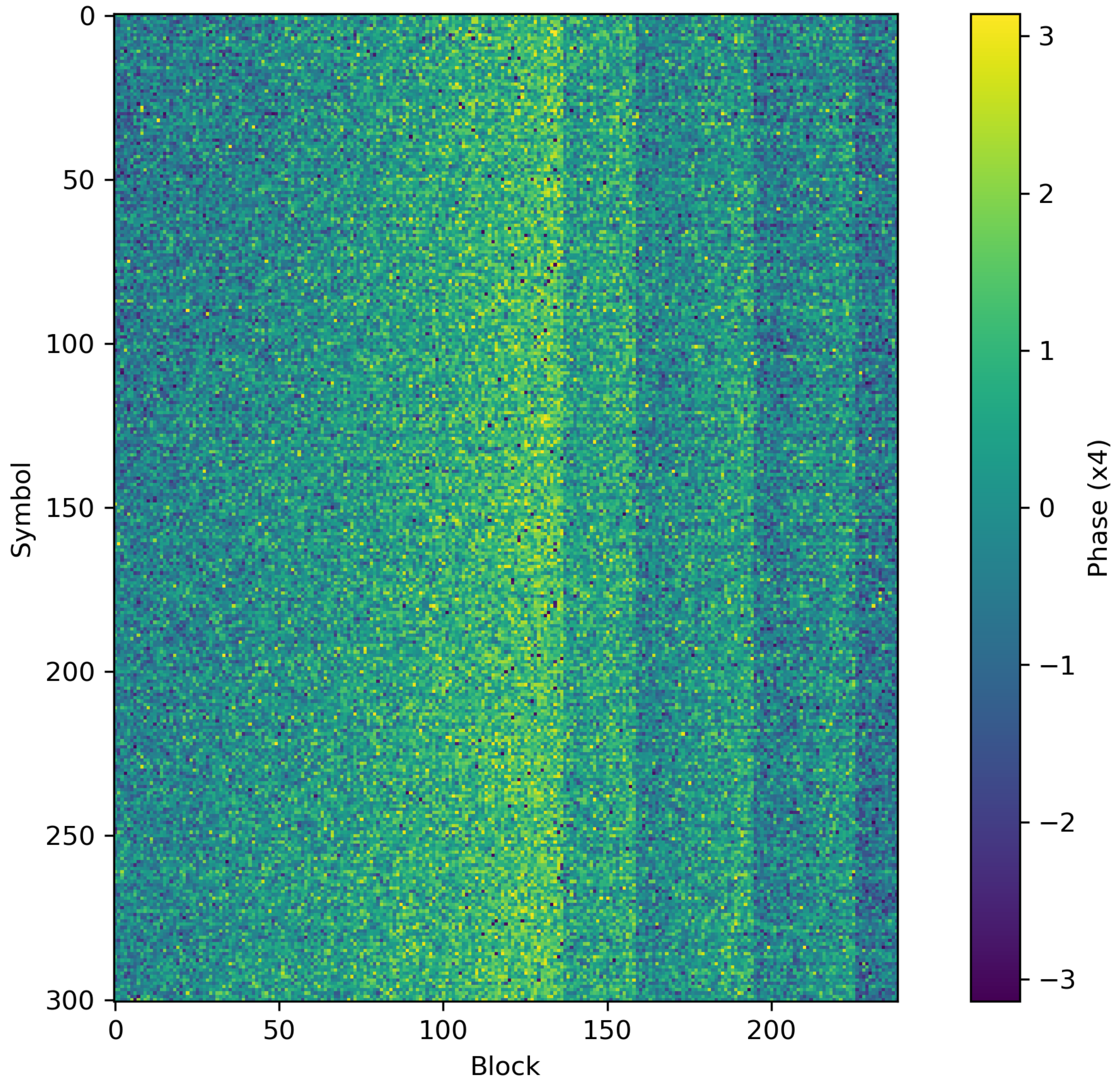
Symbol
0
50
100
150
200
250
300
Block
0
50
100
150
200
Phase (x4)
3
2
1
0
−1
−2
−3



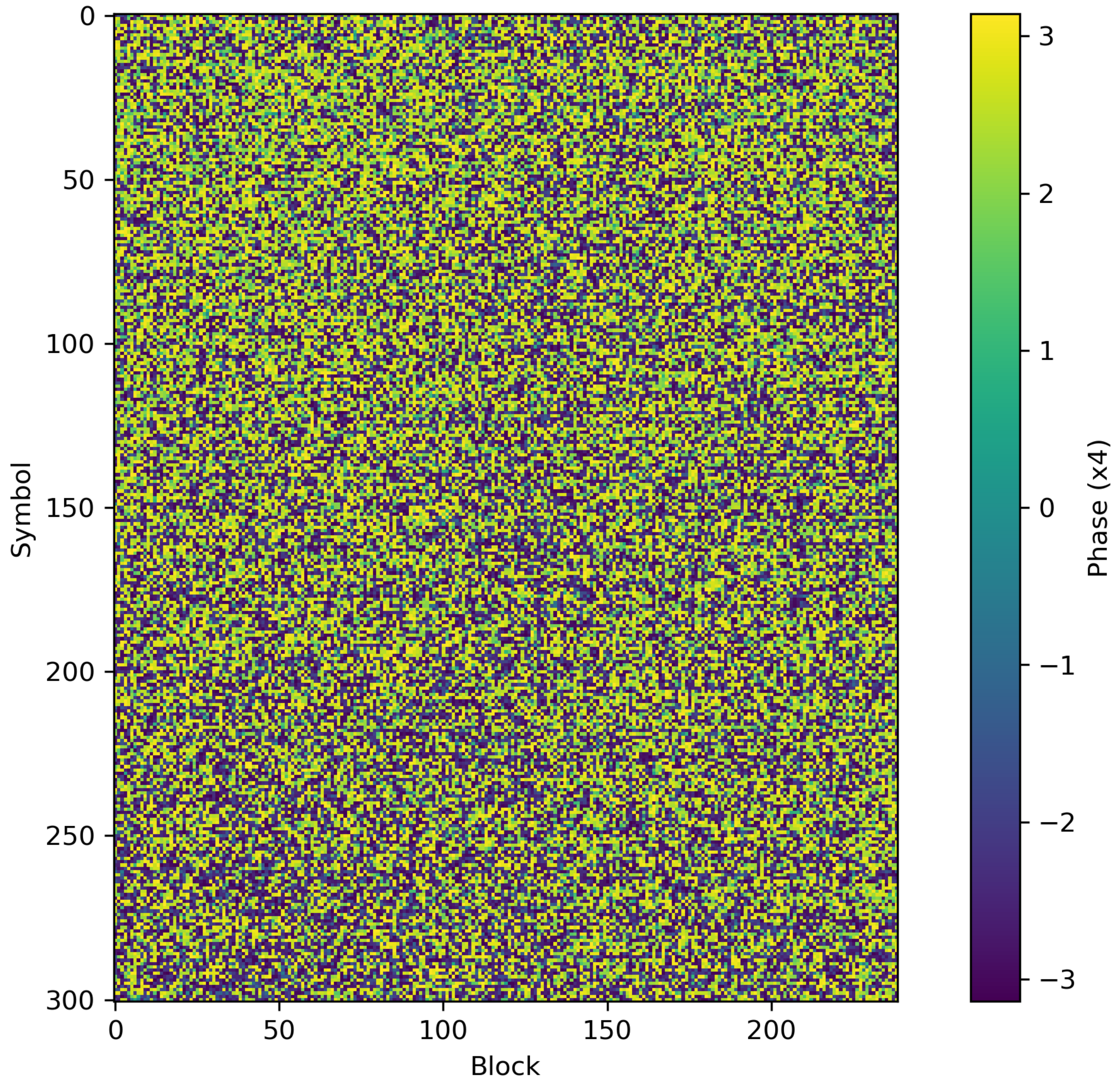
Symbol
Block
Phase (x4)
0
50
100
150
200
250
300
0
50
100
150
200
3
2
1
0
−1
−2
−3



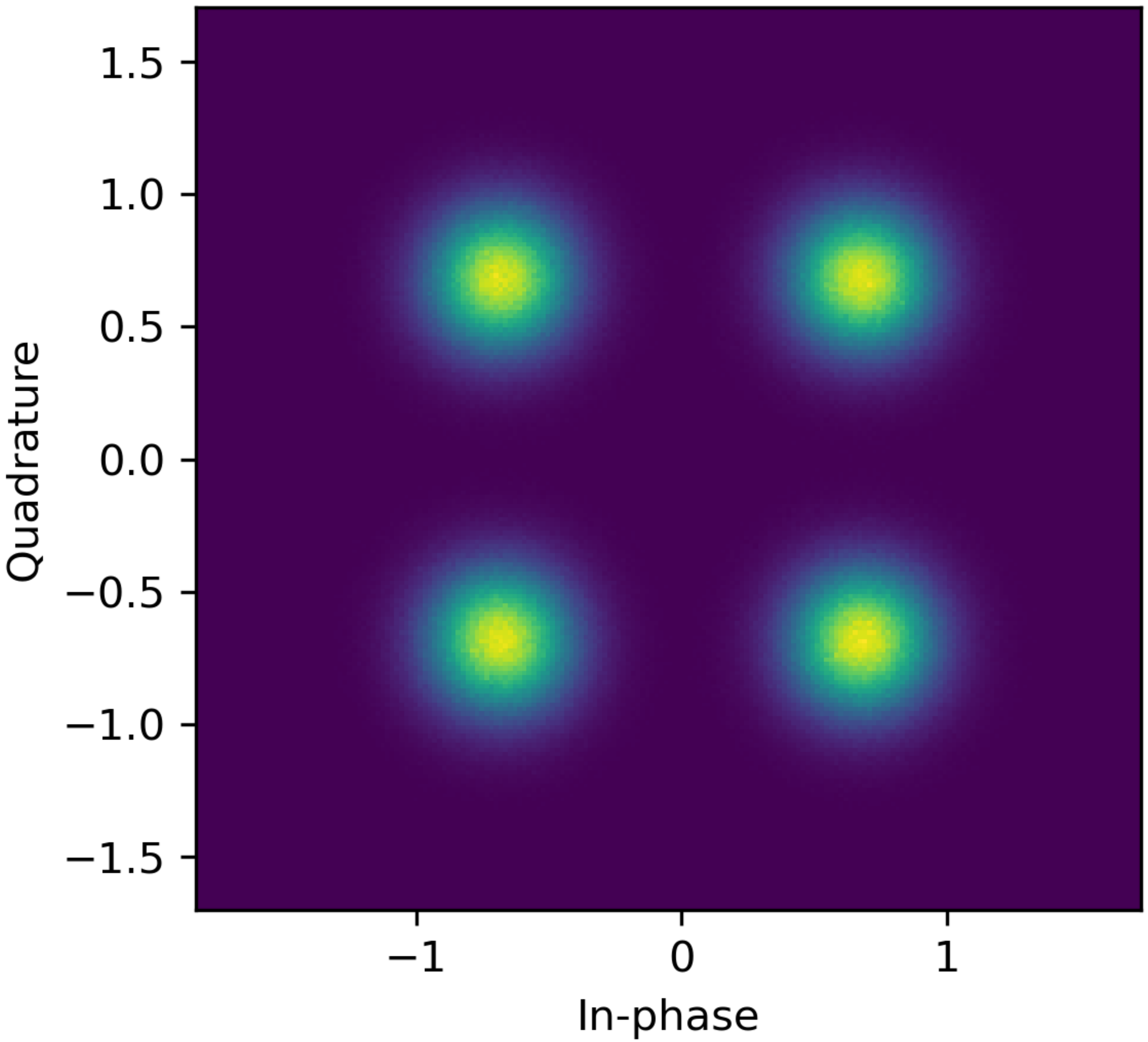
Symbol
Block
Phase (x4)
0
50
100
150
200
250
300
3
2
1
0
−1
−2
−3



Symbol
Block
Phase (x4)
0
50
100
150
200
250
300
0
50
100
150
200
3
2
1
0
−1
−2
−3



Symbol
Block
Phase (x4)



1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Quadrature
−1
0
1
In-phase