Pseudorange Bias From Inter-Signal Interference: the QZSS L5-L5S Case

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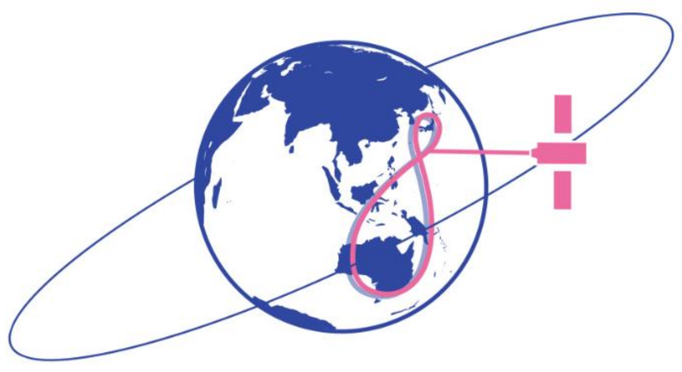
Abstract

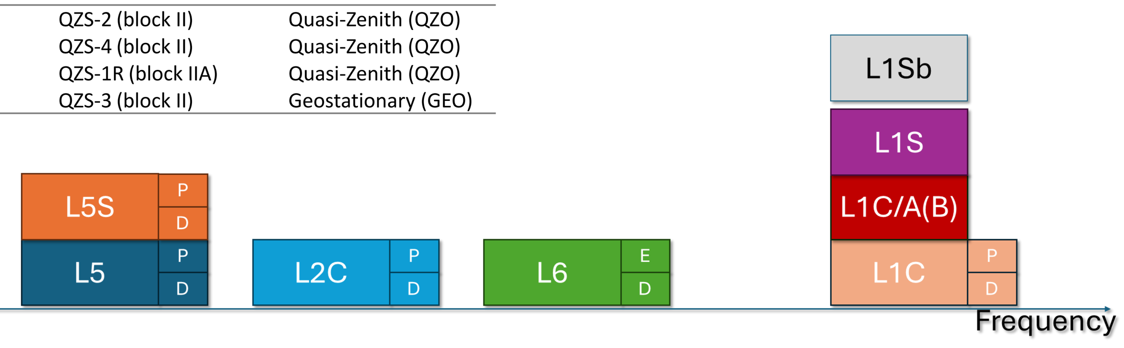
Analysis of QZSS L5 pseudorange biases reveals decimeter-level variations over the satellite passes, a phenomenon that is not observed on any other GNSS signal and that complicates the use of QZSS L5 in high-accuracy applications. This poster provides insights into this QZSS peculiarity. It is shown that the bias depends on the orientation of the line-of-sight vector with respect to the transmit antenna panel of the QZSS satellite, and that the amplitude of its variation is satellite dependent. The cause is identified as interference from the L5S signal transmitted by QZSS satellites at the same frequency and from a different antenna. The interference introduces a distortion of the correlation peak dependent on the primary and secondary code selected for the L5 and L5S signals and on the relative delay and phase between the received L5 and L5S signals. This distortion induces tracking biases affecting pseudoranges produced using the pilot signal component. The bias variation can be accurately modeled and compensated for if L5 and L5S measurements are available.

QZSS

- Quasi-Zenith Satellite System ("Japanese GNSS").
- 4 operational satellites (J02, J03, J04, J07).
- 8 signal types on 4 bands (L5, L2, L6 and L1).
- Like on other GNSS constellations, many QZSS signals (L5, L5S, L2C and L1C) are made up of a pilot and a data component (P/D).



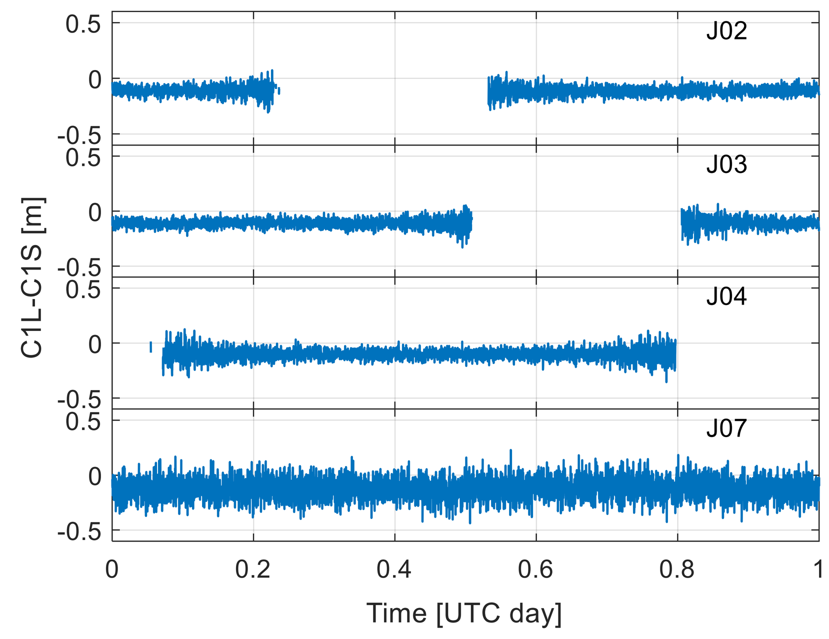
RINEX Satellite ID	PRN Number (L5 / L5S)	QZSS Satellite Name and Block Type	Orbit Type
J02	194 / 184	QZS-2 (block II)	Quasi-Zenith (QZO)
J03	195 / 185	QZS-4 (block II)	Quasi-Zenith (QZO)
J04	196 / 186	QZS-1R (block IIA)	Quasi-Zenith (QZO)
J07	199 / 189	QZS-3 (block II)	Geostationary (GEO)



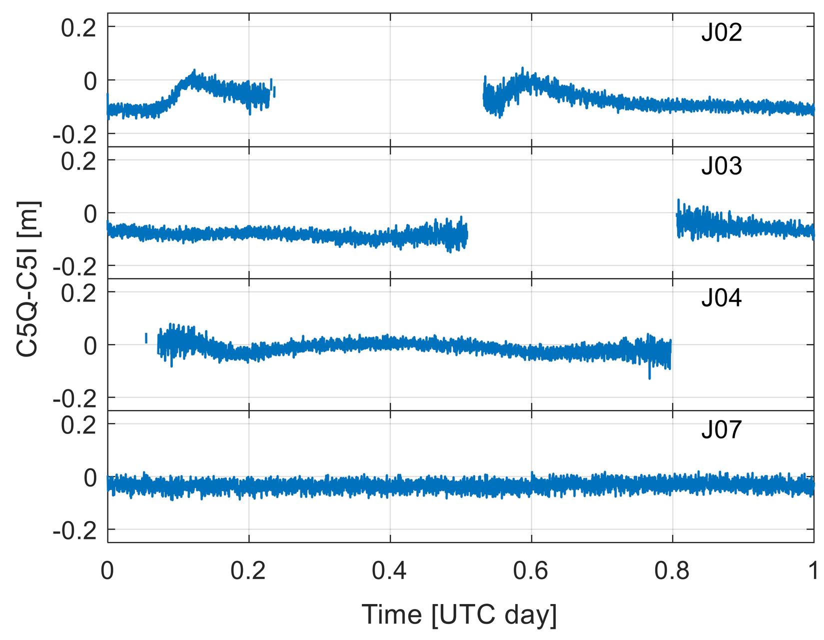
The QZSS L5 peculiarity…

- Pseudoranges taken from the pilot and data component normally only differ by a constant bias and noise. The example on the left shows QZSS L1C.
- QZSS L5 and QZSS L5S are the only known exceptions: the difference between pilot and data pseudoranges exhibits dm-level variations along the satellite pass. The QZSS L5 case is shown on the right.

QZSS L1C: stable bias (as usual for all other GNSS signals except QZSS L5)



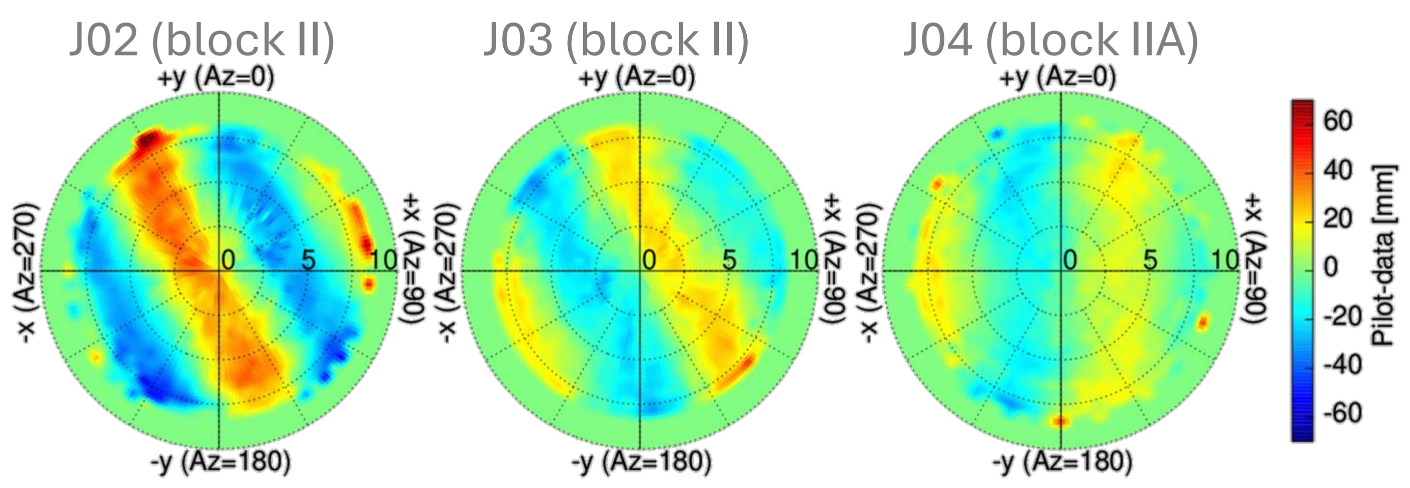
QZSS L5: bias variation over satellite pass



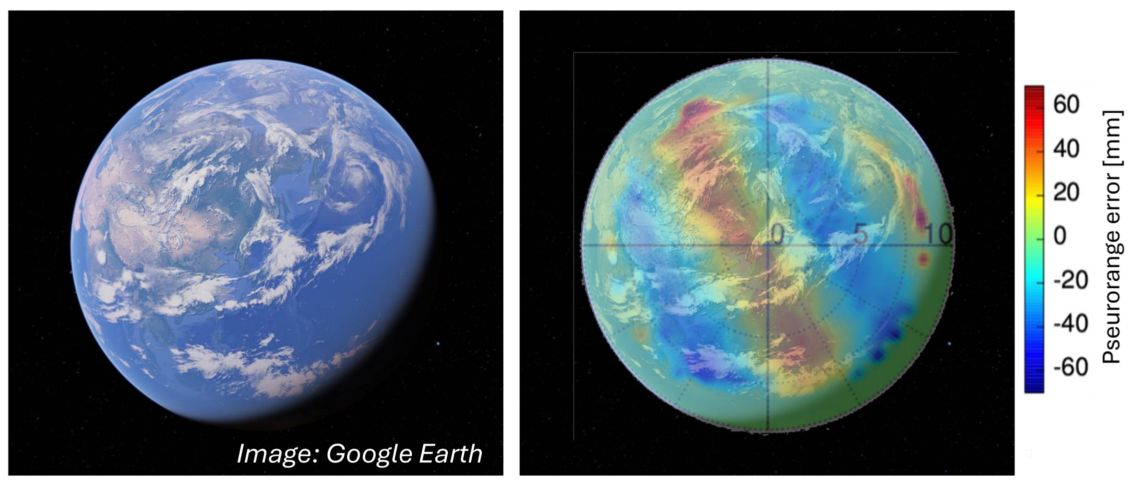
Difference between pilot and data pseudoranges for QZSS L1C (representative of the usual case), and for QZSS L5. Data from PolaRx5 in Tokyo running a modified firmware version. Data from May 29, 2024

Bias properties

- Analysis of data from the MIRAI network (https://go.gnss.go.jp/mirai/) reveals a strong dependence of the pilot-data bias on the orientation of the line-of-sight vector with respect to the QZSS satellite antenna panel.
- The magnitude of the variation depends on the QZSS satellite, J02 being the most affected (1dm peak-to-peak).
- The orientation of the fringes is different for block II and block IIA satellites.



Difference between the QZSS L5 data and pilot pseudoranges for J02, J03 and J04, averaged over eight MIRAI stations and over the whole year 2022. The polar plots describe the variation of the pseudorange bias with the azimuth and boresight angle of the satellite-to-station vector relative to the spacecraft body axes. All angles expressed in degrees

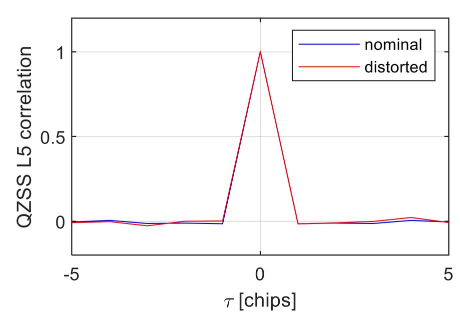


The Earth as seen from a QZSS satellite. The fringes move and rotate with the satellite orientation, leading to varying biases over the satellite passes

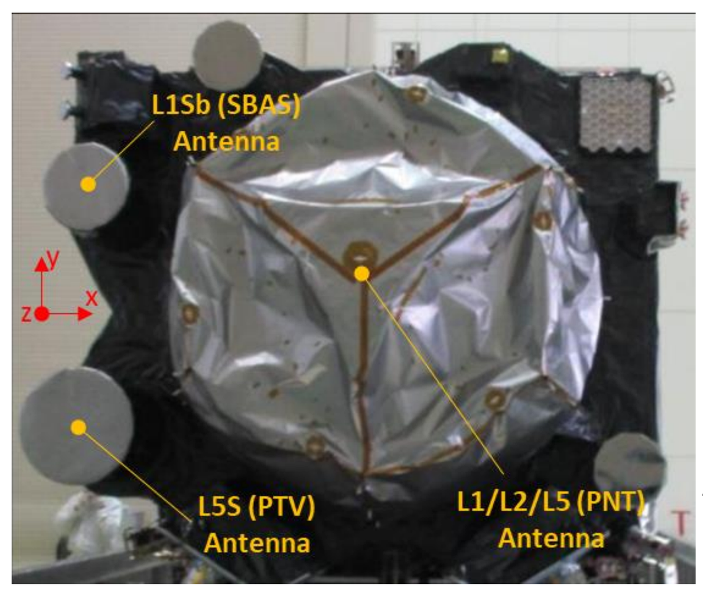
Root cause

- L5 and L5S signals are transmitted at the same frequency and with the same modulation, leading to a non-negligible level of cross-correlation.
- Both signals possess a deterministic pilot component, for which the cross-correlation is not attenuated by random bit modulation.
- The cross-correlation causes a distortion of the correlation peak, leading to biases in the pilot (or combined pilot/data) pseudoranges.
- L5 and L5S are transmitted by different antennas, so the effect depends on the relative phase and delay of the received L5 and L5S signals.
- Affected measurements (RINEX observation codes): QZSS C5Q, C5X, C5P, C5Z.

Signal	Pilot/ Data	Primary code	Secondary code	Nav bit modulation
L5-I	D	10230 chips, 10.23 Mcps	NH10: 0000110101	Yes (CNAV @ 100 sps)
L5-Q	P	10230 chips, 10.23 Mcps	NH20: 00000100110101001110	No
L5S-I	D	10230 chips, 10.23 Mcps	None	Yes (500 sps)
L5S-Q	P	10230 chips, 10.23 Mcps	NH20: 00000100110101001110	No



Small but measurable asymmetrical correlation distortion



J02 (QZS-2, block II) antenna panel

Image: JAXA

Cure

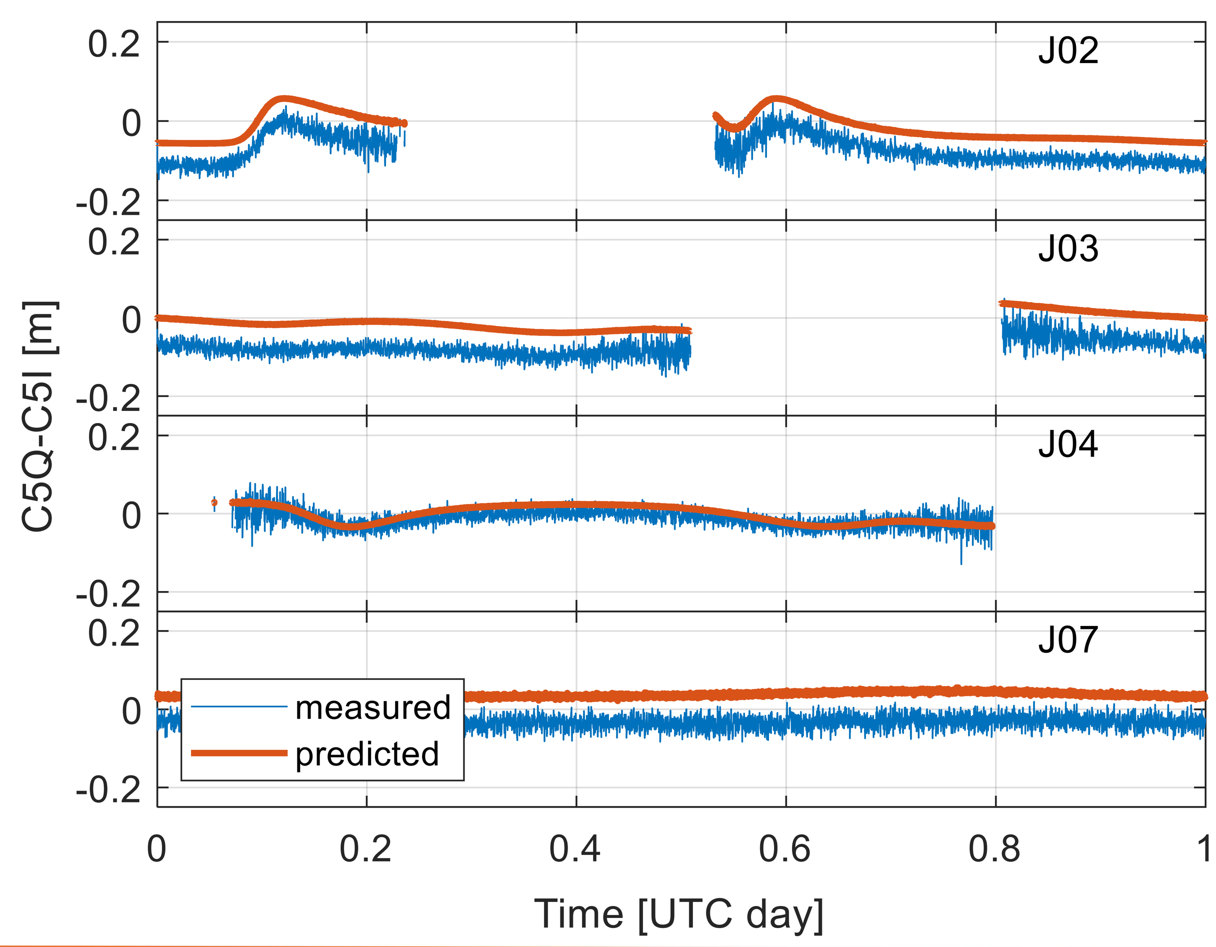
- The bias can be accurately modeled from the known pilot PRN codes.
- No need to compute the satellite orientation!
  - Relative delay is the difference in L5 and L5S pseudorange.
  - Relative phase is the difference in L5 and L5S carrier phase.
- Compensation formula:

$$\mathrm{B}[m] \cong \left(d \cdot B_0 + \mathrm{clip}\left(P_{L5} - P_{L5S}, -\frac{d{\cdot}29.3}{2}, \frac{d{\cdot}29.3}{2}\right) \cdot B_1\right) \cos\left(2\pi(\varphi_{L5} - \varphi_{L5S})\right)$$

With:

- P_{L5} and P_{L5S} the L5 and L5S pseudoranges in meters,
- φ_{L5} and φ_{L5S} the carrier phase measurements in cycles,
- d the early-late spacing in chips, d=1/3 for PolaRx5 receivers,
- B0 and B1 are satellite specific constants, see table,
- clip(*x,min,max*) returns *min* if *x*<*min, max* if x>*max*, and *x* otherwise.

QZSS Satellite	PRN Number (L5 / L5S)	B_0 [m]	B_1 [m]
J01 (QZS-1)	193 / 183	0.1611	-0.0042
J02 (QZS-2)	194 / 184	0.1236	0.0050
J03 (QZS-4)	195 / 185	-0.0855	-0.0031
J04 (QZS-1R)	196 / 186	0.0056	0.0162
J05 (QZS-5)	197 / 187	0.0481	0.0091
J06 (NA)	198 / 188	-0.1092	-0.0027
J07 (QZS-3)	199 / 189	-0.0865	-0.0150
J08 (QZS-6)	200 / 190	0.2014	0.0027
J09 (QZS-7)	201 / 191	0.0200	0.0065
J10 (NA)	202 / 192	-0.0369	0.0002



Difference between pilot and data pseudoranges for QZSS L5, and predicted effect of the L5-L5S pilot cross-correlation. The residual offset between the red and blue lines reflects inter-signal biases in the satellite.

Conclusions

- When two deterministic (pilot) signals are transmitted at the same frequency from the same satellite, they are likely to interfer with each other, causing tracking biases.
- If they are transmitted from two different antennas, this tracking bias changes with the satellite orientation.
- An example is given by QZSS L5 and QZSS L5S.
- The inter-signal interference is deterministic and can be accurately modeled.
- Compensation is possible if measurements from L5 and L5S are available.

Additional details and theoretical derivations in:
Sleewaegen, J.M., Montenbruck, O. & Steigenberger, P. Pseudorange bias from inter-signal interference: the QZSS L5-L5S case. GPS Solut 27, 150 (2023). https://doi.org/10.1007/s10291-023-01490-w