Optical Pattern of Life Analysis Library (OPAL)

Michael Ling, Yang Yang, Flora Salim

SRN Research Pilot Project (Round 1, 2024–25) · UNSW · Macquarie University · University of Adelaide
Optical observations: Macquarie University; AIUB, University of Bern

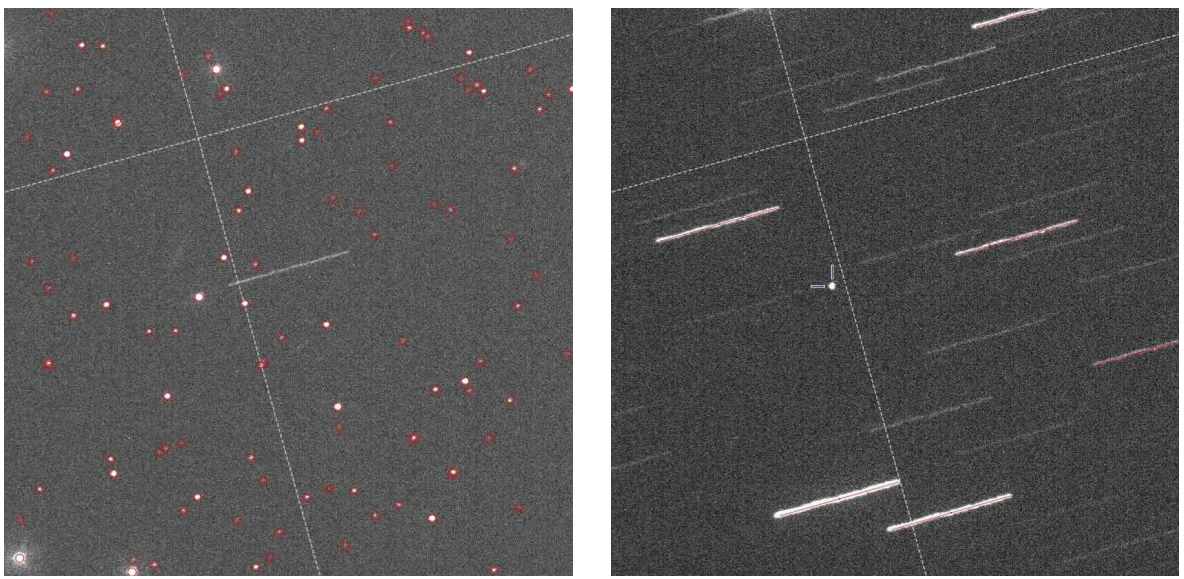
Background

- GEO hosts ∼590 operating satellites carrying comms, weather and defence services
- Satellites exhibit **pattern-of-life** (PoL)
- Current PoL analysis models → 6-DOF states
- Optical infrastructure is widely adopted → 2-DOF
- **OPAL:** a dataset to train transformers that classify PoL, early flagging of anomalous behaviour
- **Question:** can raw optical angles (RA/Dec) alone classify PoL?

Optical angles

What an optical observation gives

- Each frame gives the satellite's position as a time and two angles (t, α, δ)
- **Right ascension** α and **declination** δ: the satellite's place on the celestial sphere, i.e. longitude and latitude on the sky



Images: Macquarie University

Recent progress

Minority patterns are absent from acquired real data — **synthetic data from SPLID**

Irregular cadence: weather, daylight, tasking — **tracklet synthesis**

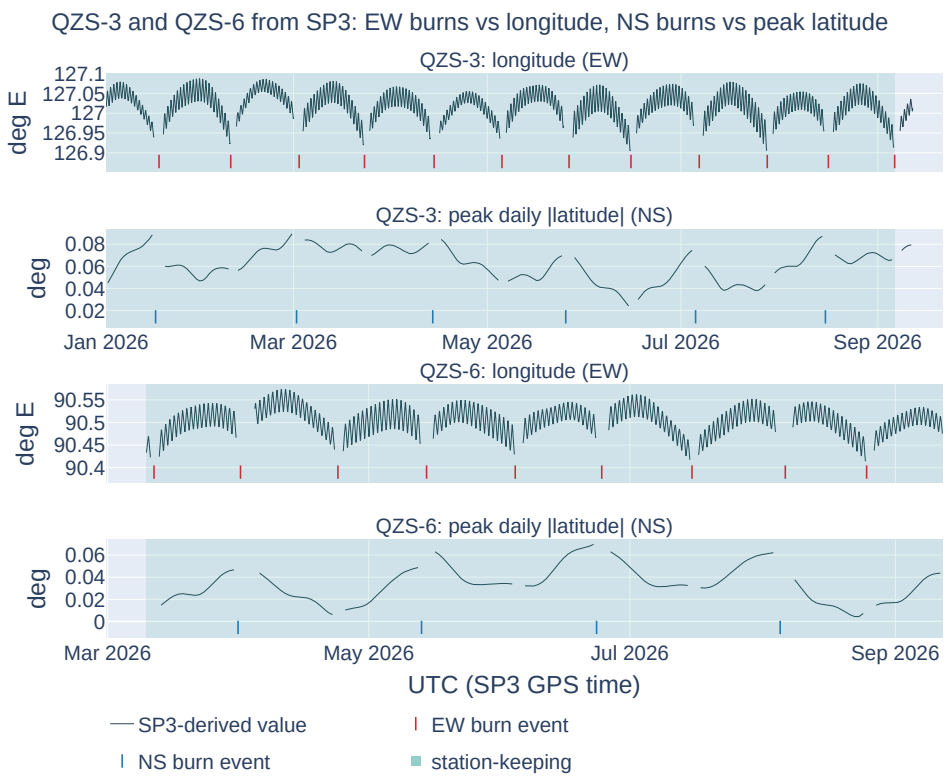
Limited 2-DOF angles v.s. 6-DOF state / station local frame incompatibility — **Cartesian PAR**

Classify PoL from irregular optical tokens — **TS transformer**

Minority patterns

Challenge 1 · Minority patterns are absent from real data

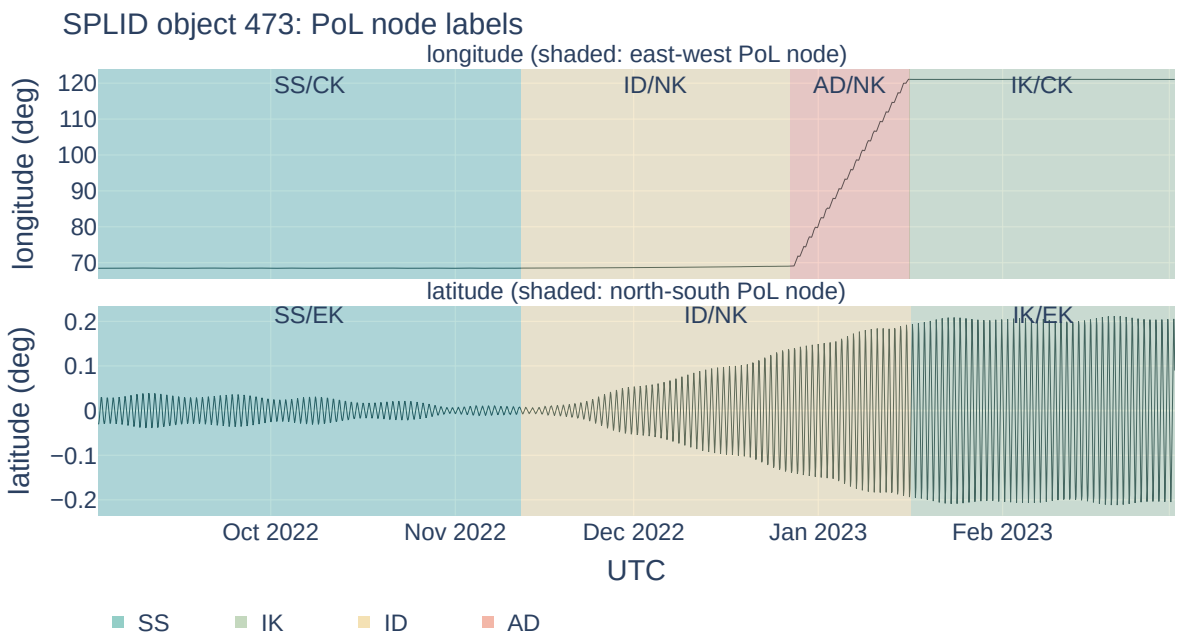
- Real Fengyun and QZSS windows are dominated by a single PoL
- QZSS is a single PoL mode; Fengyun has a handful of drift or relocation episodes



Minority patterns

Solution · SPLID synthetic data

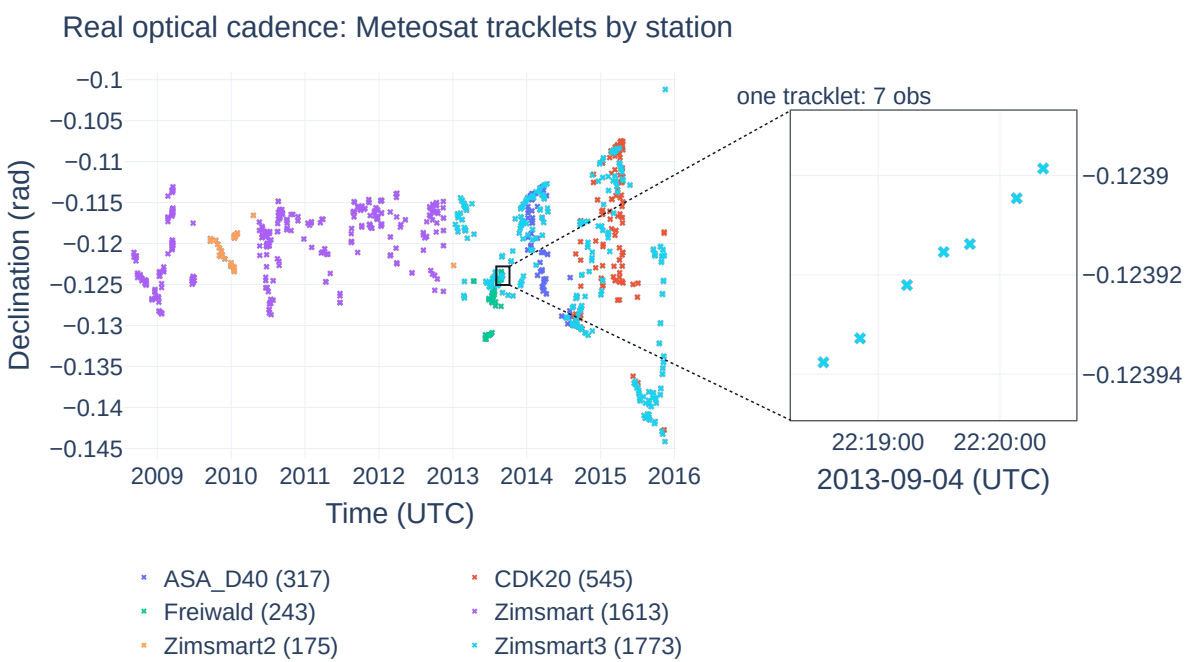
- SPLID adds ∼2000 simulated GEO series including many rarer PoL modes
- **Limitation**: Contains full trajectory data at 2 hr sampling cadence



Irregular cadence

Challenge 2 · Irregular cadence

- Real tracklets are short, irregular bursts
- Visibility affected by weather, daylight and tasking
- TLE, and ephemeris products generally cadence is on order of days

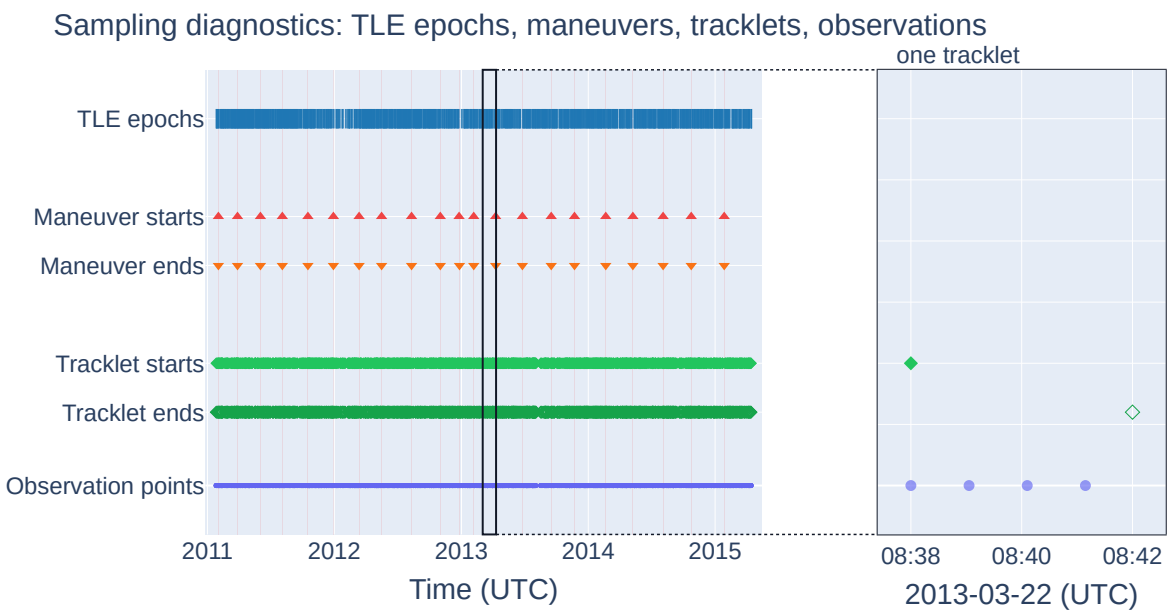


Data: AIUB, University of Bern

Irregular cadence

Solution · Tracklet synthesis

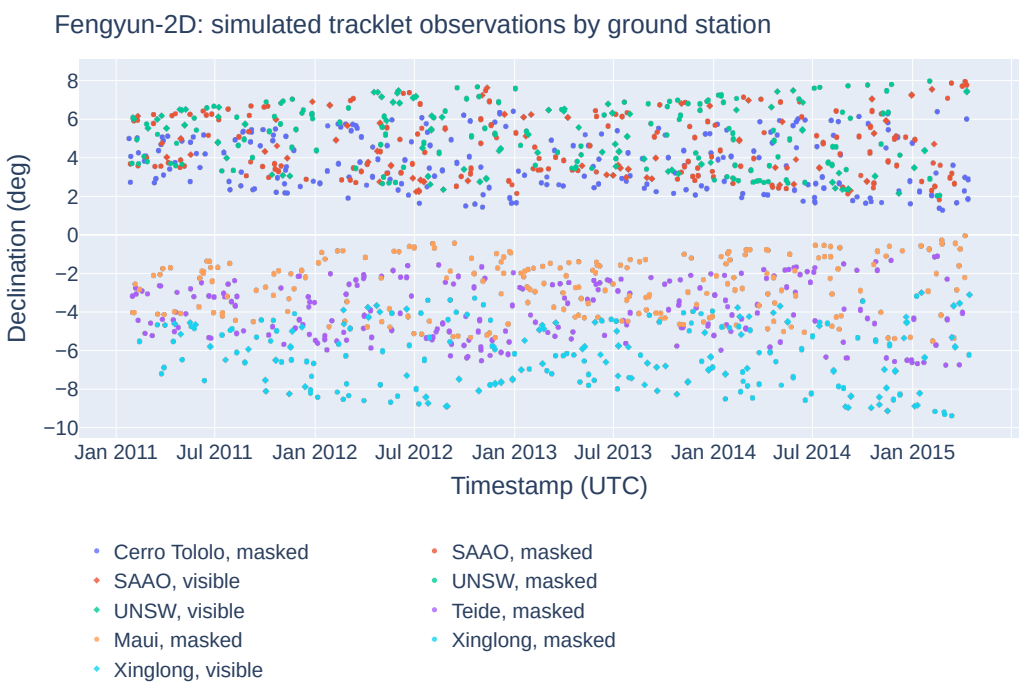
- Each station samples its own starts, cadence and duration
- Mask: elevation, Sun altitude and LoS
- Multiple support sampling methods: SGP4 (TLE), HiFi numerical propagators (SP3)



2-DOF to 6-DOF / Station Reference Frame

Challenge 3 · Limited DOF and Incompatible Frames

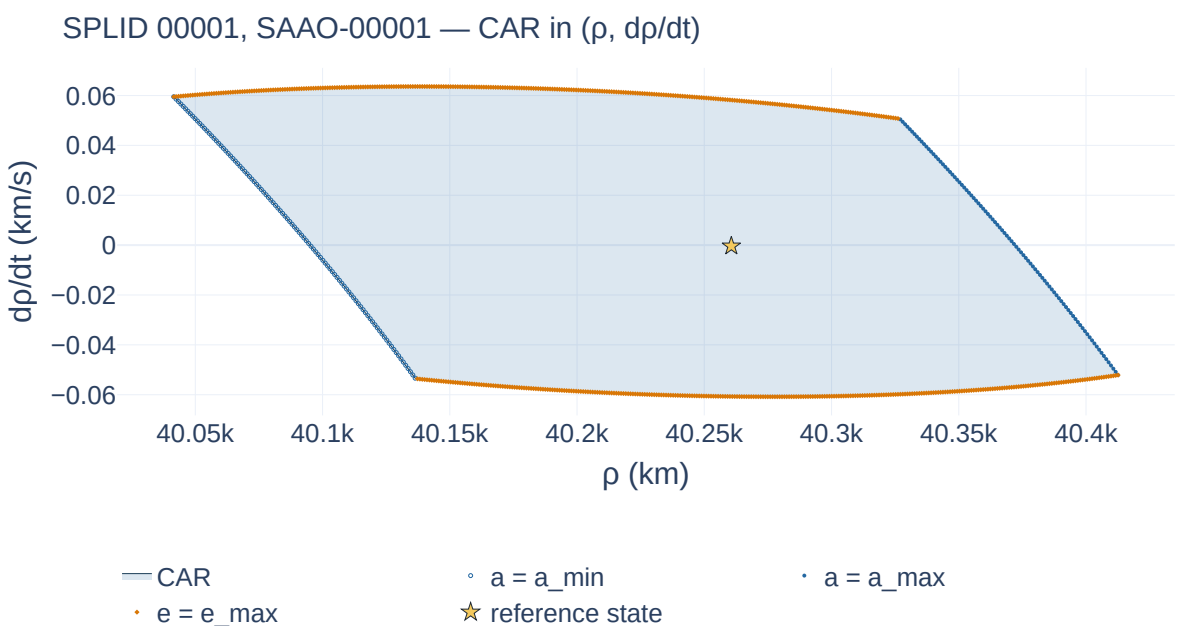
- A tracklet gives $\left(\alpha, \delta, \dot{\alpha}, \dot{\delta}\right)$ and no range
- Current PoL models use 6-DOF states
- RA/Dec from one station frame cannot be compared to another station



2-DOF to 6-DOF / Station Reference Frame

Solution · PAR on Common Frame

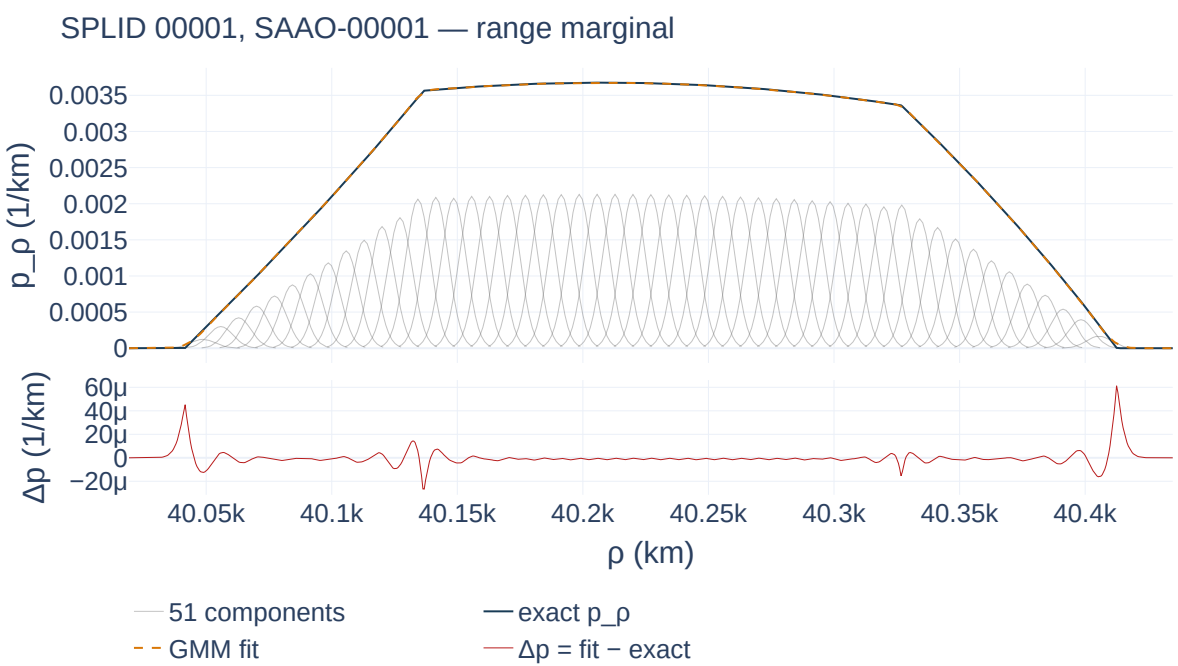
- Constrained admissible region over $(\rho, \dot{\rho})$ on a prior
- Adapted from DeMars & Jah (2013), which represents the CAR as a Gaussian-mixture PAR
- Transform the $\left(\rho, \dot{\rho}, \alpha, \dot{\alpha}, \delta, \dot{\delta}\right)$ to Cartesian $(x, y, z, \dot{x}, \dot{y}, \dot{z})$ for comparison across stations



2-DOF to 6-DOF / Station Reference Frame

Solution · PAR on Common Frame

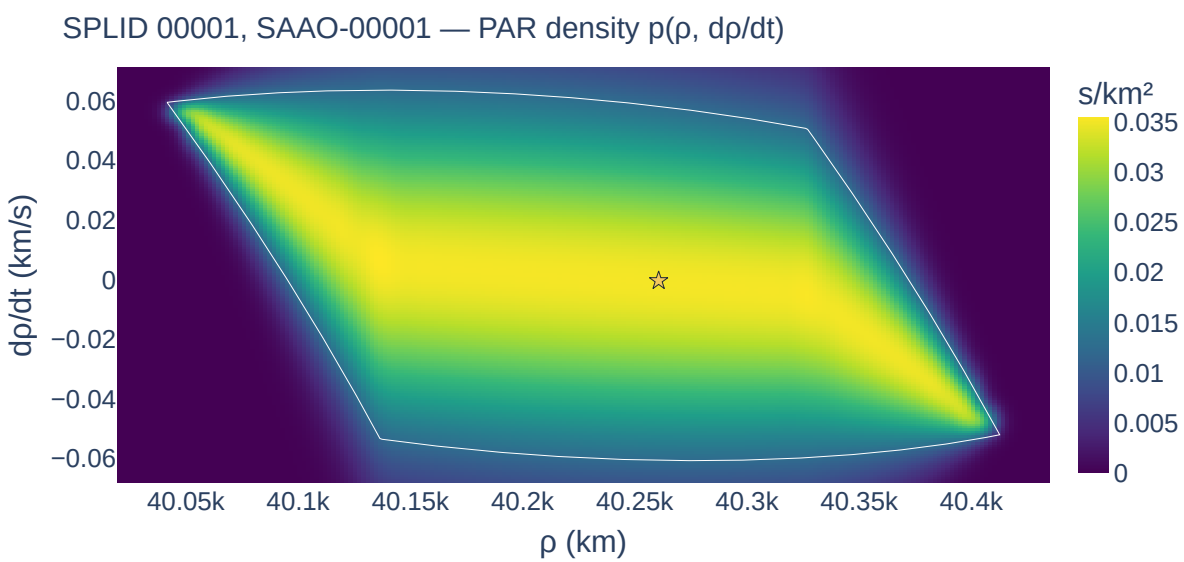
- Constrained admissible region over $(\rho, \dot{\rho})$ on a prior
- Adapted from DeMars & Jah (2013), which represents the CAR as a Gaussian-mixture PAR
- Transform the $\left(\rho, \dot{\rho}, \alpha, \dot{\alpha}, \delta, \dot{\delta}\right)$ to Cartesian $(x, y, z, \dot{x}, \dot{y}, \dot{z})$ for comparison across stations



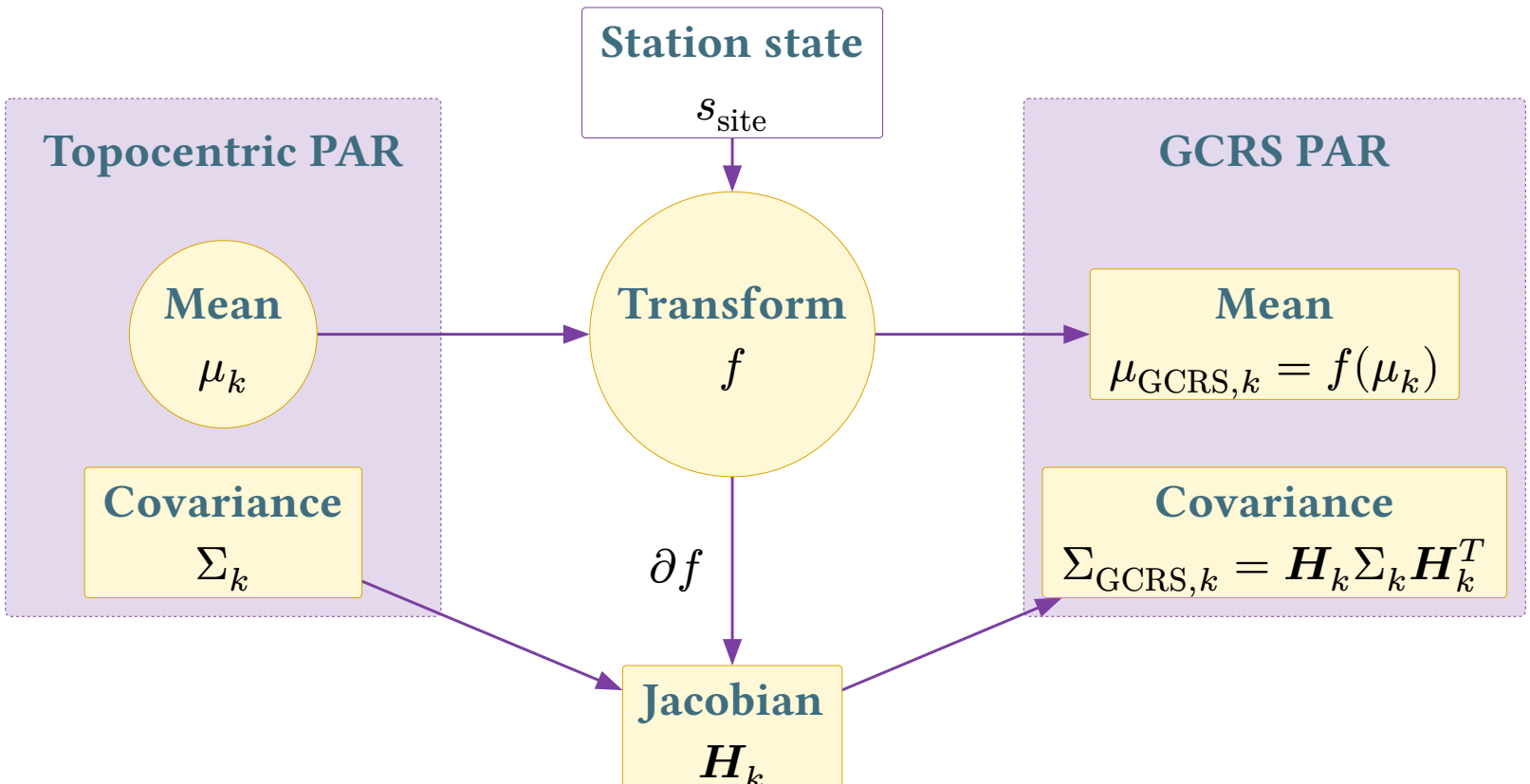
2-DOF to 6-DOF / Station Reference Frame

Solution · PAR on Common Frame

- Constrained admissible region over $(\rho, \dot{\rho})$ on a prior
- Adapted from DeMars & Jah (2013), which represents the CAR as a Gaussian-mixture PAR
- Transform the $\left(\rho, \dot{\rho}, \alpha, \dot{\alpha}, \delta, \dot{\delta}\right)$ to Cartesian $(x, y, z, \dot{x}, \dot{y}, \dot{z})$ for comparison across stations



Cartesian PAR



Results

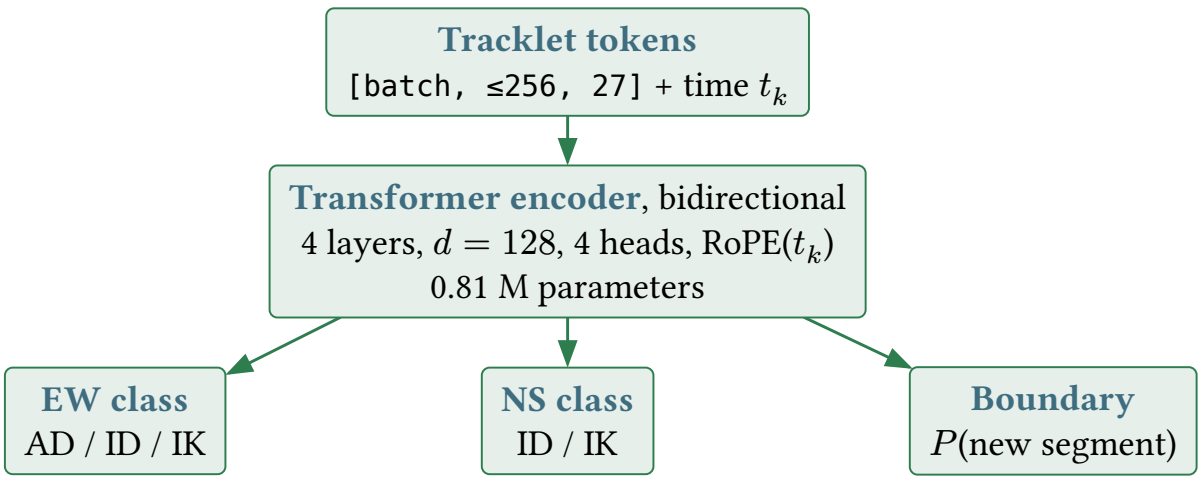
Data repo contents

Directory	Size	Contents
`splid/`	4.3 GB, 10k files	SPLID GEO series: `phase_1`, `phase_1_v2`, `phase_1_v3`, `phase_2` (training 1,900 files, test 500), warmup sets
`qzss/`	239 MB	CDDIS MGEX precise orbits ledger, OHI
`meteosat/`	281 MB	Meteosat observations and processed files
`fengyun/`	8 MB	FengYun OHI and TLE

PoL transformer

Model · bidirectional encoder over PAR tokens

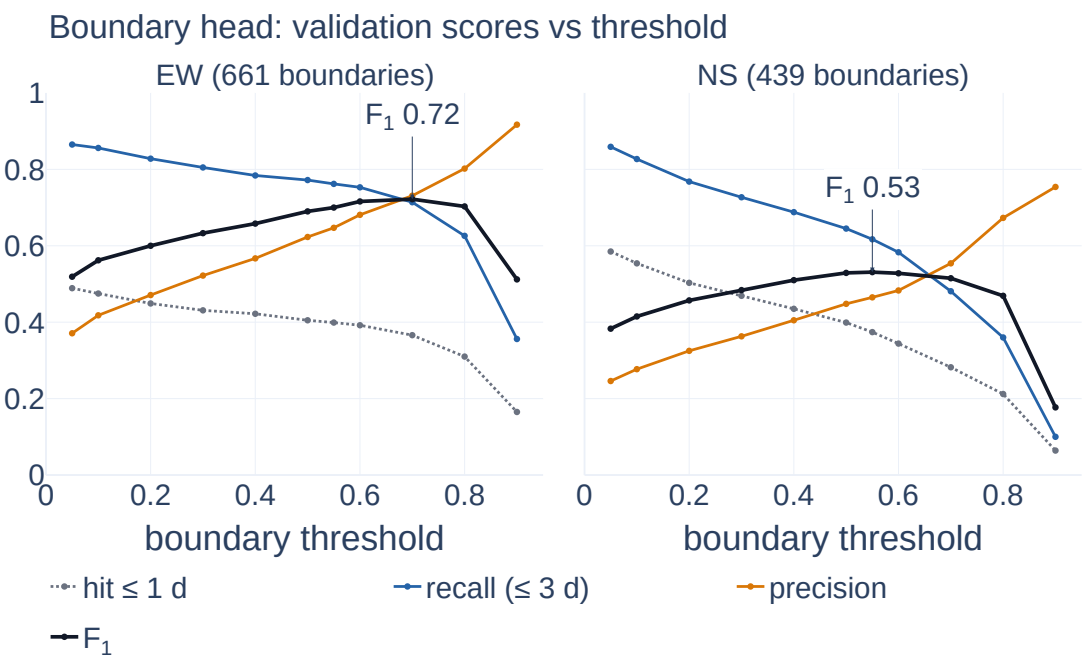
- 1,900 SPLID objects, ∼181 d, 6 stations, 3 arcsec noise; split by object 1,520 / 380
- One token per tracklet: GCRS PAR
- ∼270 tokens per object, median 0.5–0.6 d apart
- RoPE on continuous time



Boundary detection

Result · node boundaries within 3 days

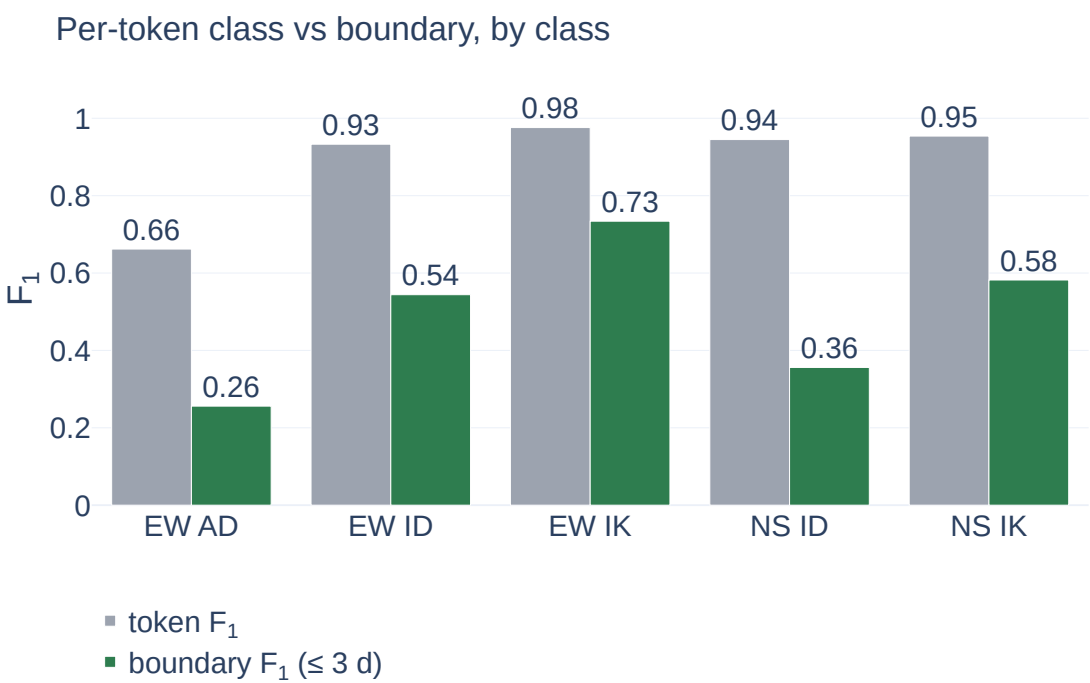
- Hit: a predicted boundary within 3 d of a true one
- **EW F_1 0.72** (threshold 0.7); 37% of boundaries hit within 1 d
- **NS F_1 0.53** (threshold 0.55); about half of NS predictions are false positives



Classes vs boundaries

Result · token accuracy is not boundary accuracy

- Token macro-F_1: 0.86 EW, 0.95 NS
- Boundaries from those tokens are worse: shifting a boundary by days costs few tokens
- F_1: IK > ID > AD



Findings

Finding · label placement and node labels drive boundary F_1

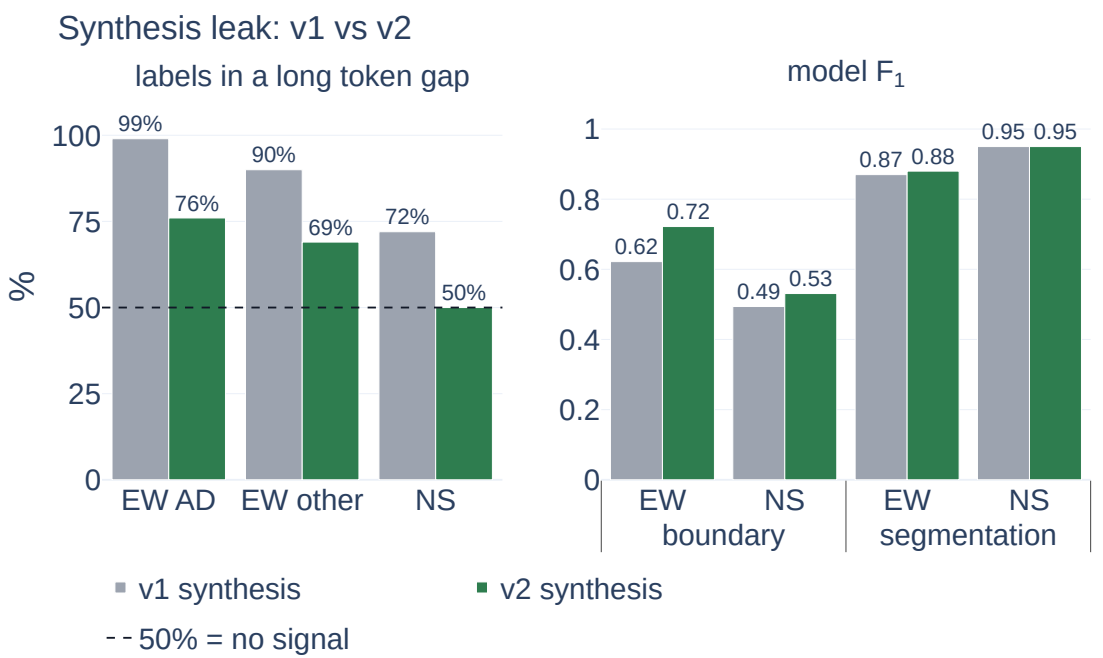
- Boundary target on the first token after a label, not the label epoch: EW 0.04 → 0.42
- Node labels: most errors were chemical vs electric with the right node
- Leak-reduced synthesis (v2, next slide) improved the model: EW hits within 1 d 0.03 → ∼0.4



Findings

Finding · removing a synthesis leak improved boundaries

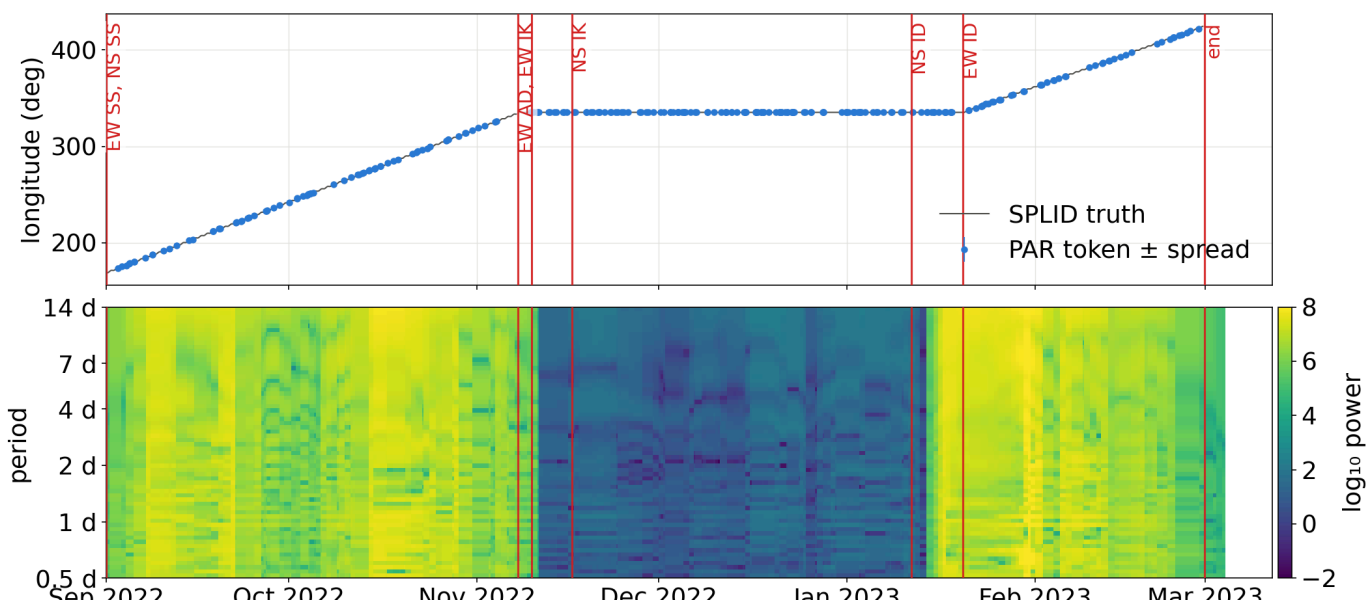
- **Synthesis leak:** v1 had no tracklets inside manoeuvre windows, so token gap length as the only score (no learned model) found AD with AUC 0.99. v2: NS leak gone, weak EW leak remains
- v2 raised boundary F_1; token F_1 about unchanged



Next steps

Next · ViT on spectral inputs

- **ViT:** SegFormer (MiT-b0) on spectrograms of the PAR tokens



Questions

Supported by an SRN Research Pilot Project grant (Round 1, 2024–25). Optical observations from Macquarie University and the Astronomical Institute of the University of Bern (AIUB).