Constellation Performance and Monitoring

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(WITH HELP FROM MANY COLLEAGUES)

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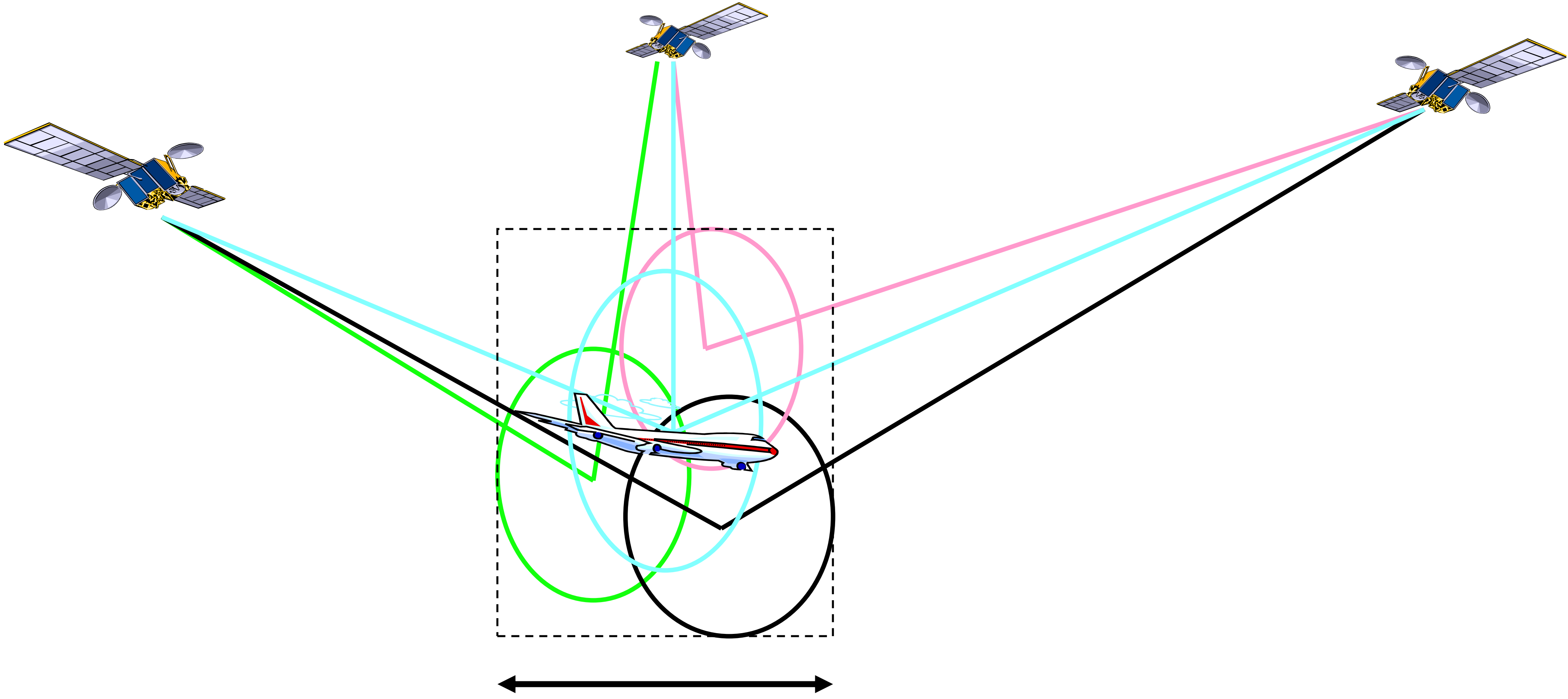
Motivation

- Safety-of-life GNSS-based systems depend on satellites having well characterized nominal behavior coupled with small probabilities of having faults
- Nominal errors are described by a Gaussian overbounding distribution (b_{nom}, σ_{URA})
- The probabilities that faults will occur must be bounded by a specified model
  - Independent satellite faults
  - Common cause constellation faults
- The determination and assurance of these parameters is the focus of this presentation

Constellation Monitoring Resources

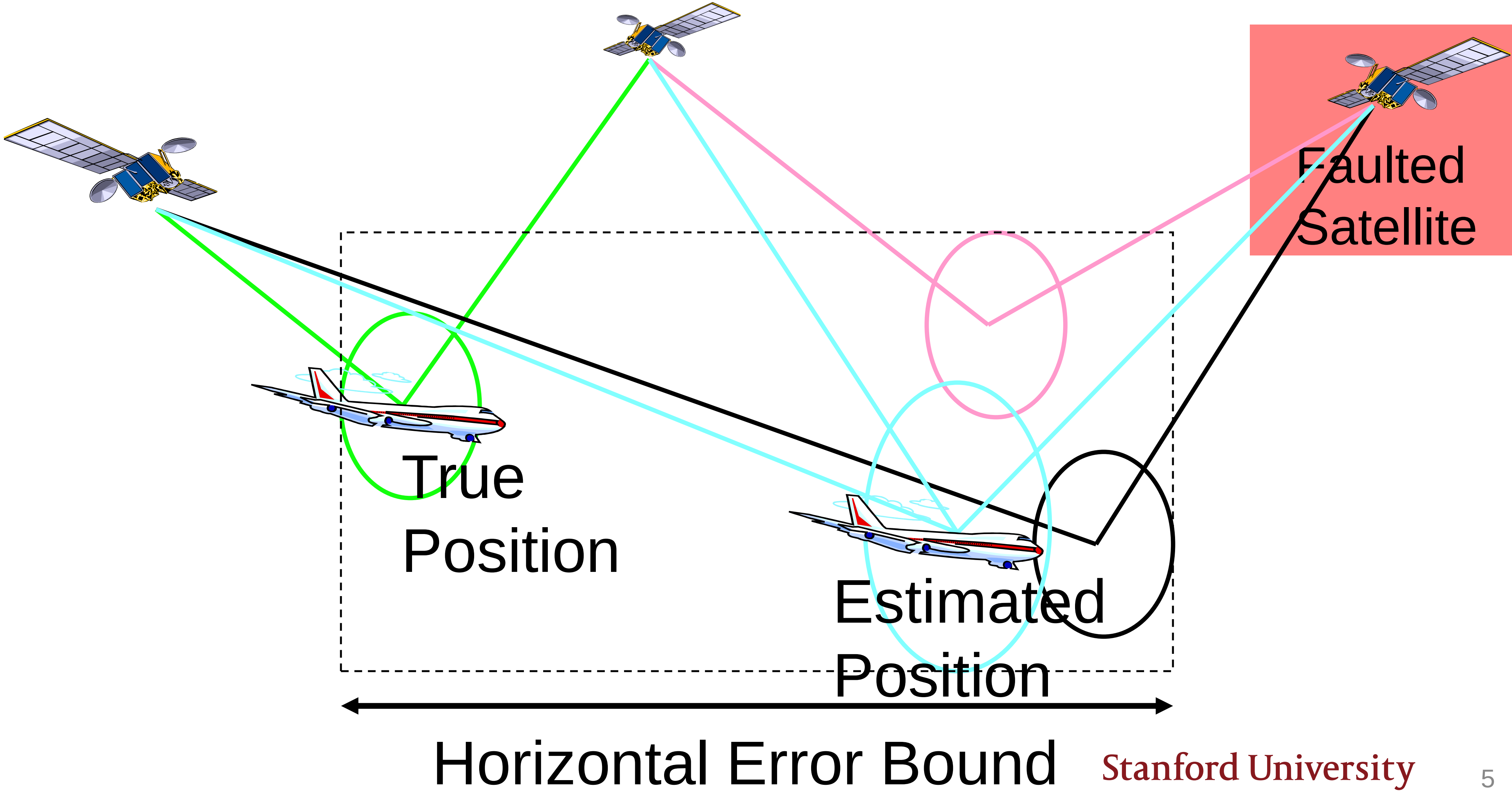
- FAA performance analysis (PAN) reports
  - https://www.nstb.tc.faa.gov/DisplayArchive.htm
- GPS SPS performance analysis yearly reports
  - https://www.gps.gov/systems/gps/performance
- Galileo quarterly OS performance reports
  - https://www.gsc-europa.eu/electronic-library/performance-reports
- GLONASS Status
  - https://www.glonass-iac.ru/en/user_performance/
- BDS
  - http://en.beidou.gov.cn/SYSTEMS/Monitoringandevaluation/

RAIM Protection



Horizontal Error Bound

RAIM Protection



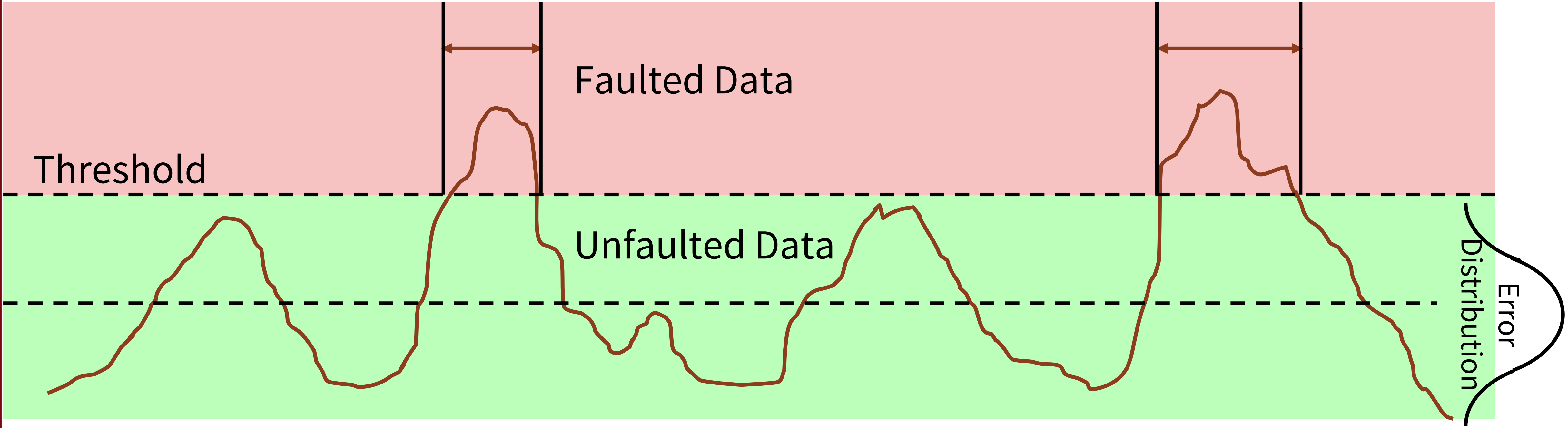
Fault Probabilities

- The satellite fault probabilities can be bounded by two fault probability bounds: P_{sat} and P_{const}:
  - P_{sat} is the probability that an individual satellite is faulted at any time
    - May be different for each satellite or all satellites may use the same numerical upper bound
  - P_{const} is the probability that any single cause leads to simultaneous faults on more than one satellite
    - May only affect 2 satellites or may affect the whole constellation
    - One single upper bound is used to cover all possible fault cases
- These two numbers may be used to bound the likelihood of all possible fault modes

Fault Rates and Fault Probabilities

- There are two related concepts: fault rate and fault probability
  - Fault rate is the number of expected times that a fault is expected to initiate in a given time – it has units of faults per hour
  - Fault probability is the likelihood of experiencing a fault right now
- They ask two related questions:
  - Fault rate asks: How many times will the error change from below the fault threshold to above it in any given length of time
  - Fault probability asks: If I measure the error right now, how likely is it to be above the fault threshold
- These are related by the Mean Fault Durations (MFD)
  - $P_{sat} = MFD_{sat} \times R_{sat}$
  - $P_{const} = MFD_{const} \times R_{const}$

R_{sat}, P_{sat} and MFD

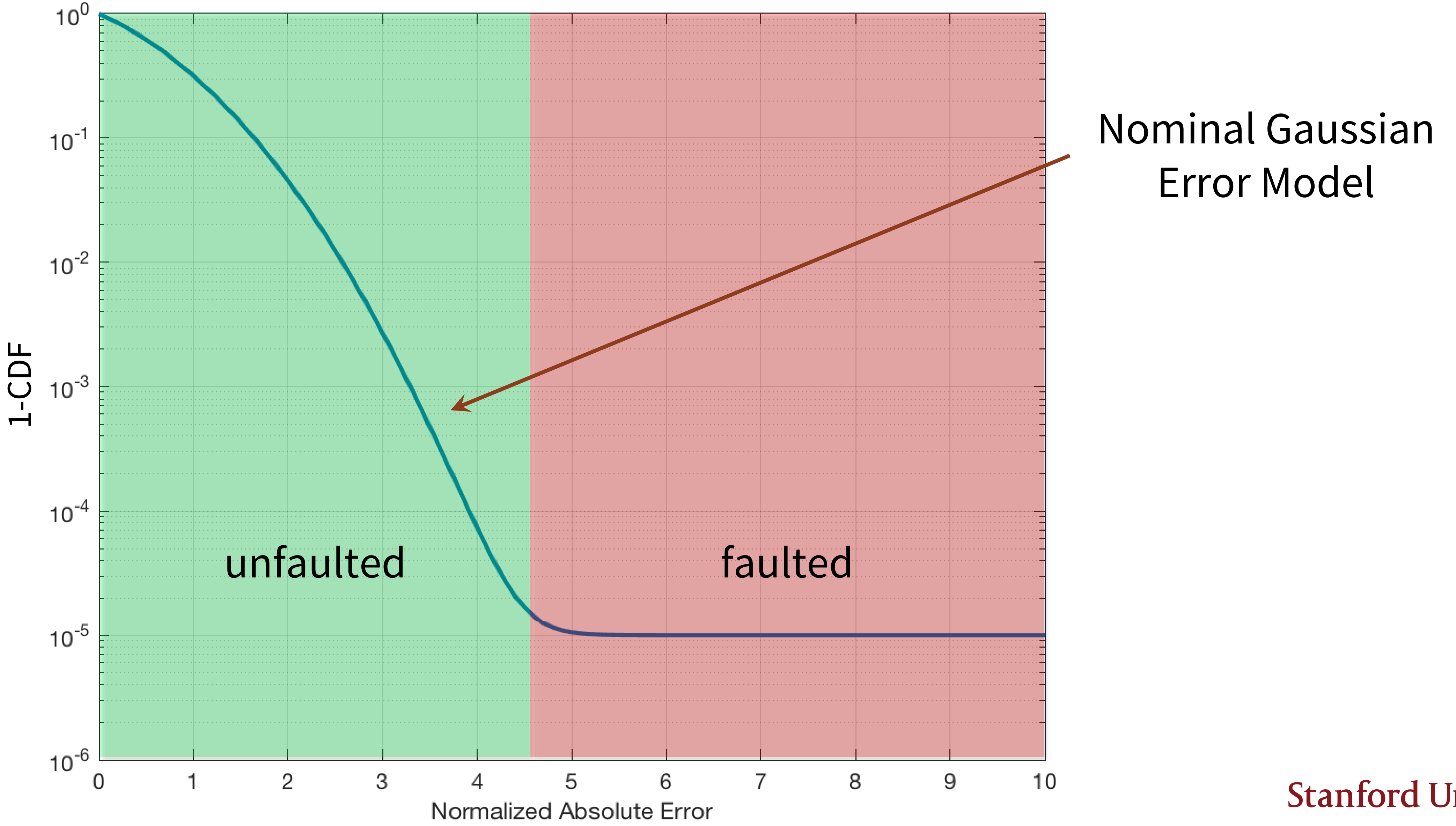


R_{sat} counts the number of upward crossings of the threshold in a given time period

MFD is used to indicate the mean fault duration and is the total length of time that the errors are above the threshold divided by the number of upward crossings

P_{sat} is the fraction of time spent above the threshold and equals R_{sat} x MFD

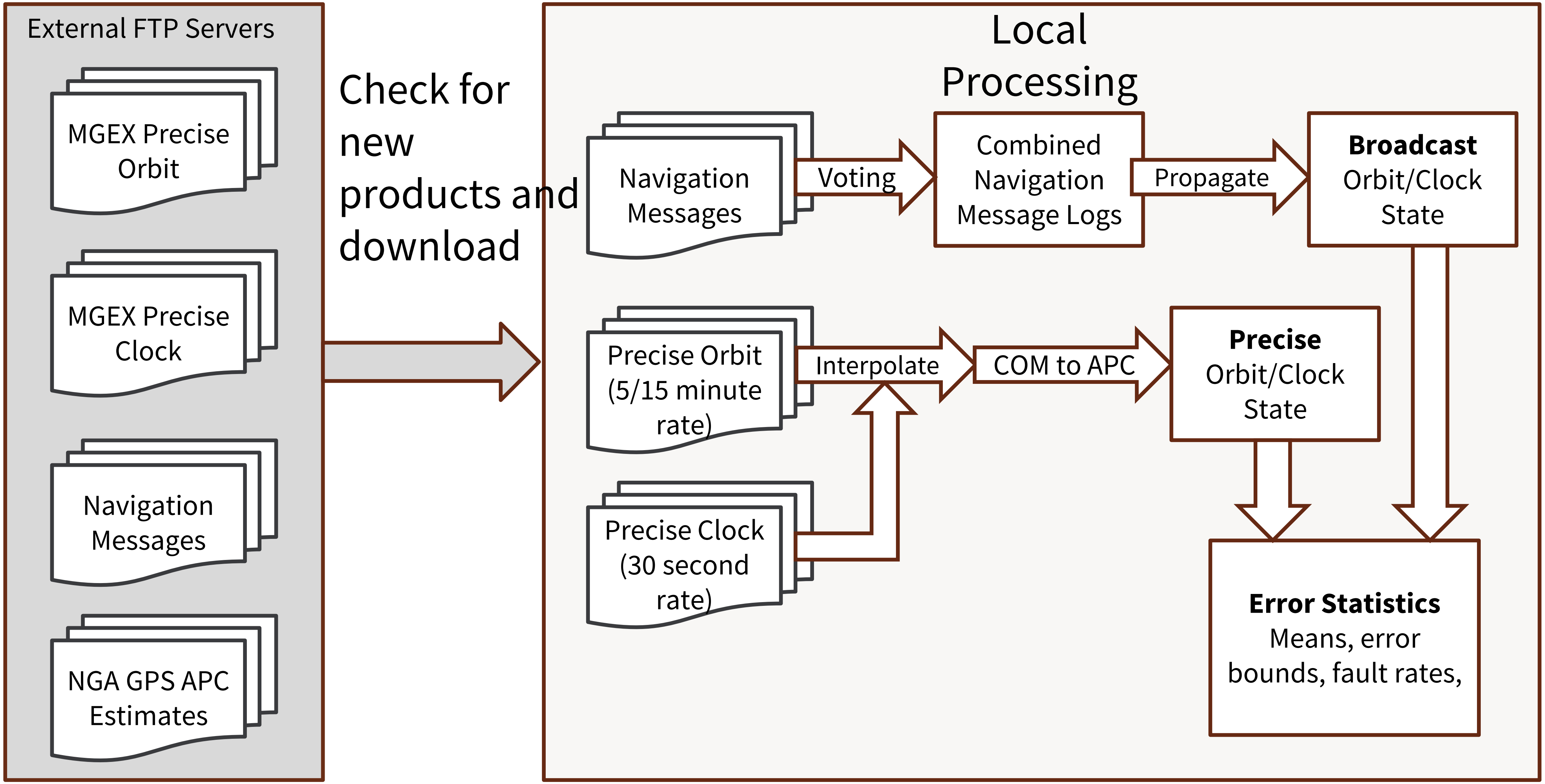
Signal-In-Space Error Distribution



Constellation Integrity Commitments

	GPS	GLONASS	Galileo	BDS
P_{const}	1×10^{-8}	1×10^{-4}	2×10^{-4}	6×10^{-5}
P_{sat}	1×10^{-5}	1×10^{-4}	3×10^{-5}	1×10^{-5}
R_{const}	1×10^{-8}/hr	1×10^{-5}/hr	1×10^{-4}/hr	6×10^{-5}/hr
R_{sat}	1×10^{-5}/hr	3.4×10^{-5}/hr	2×10^{-5}/hr	1×10^{-5}/hr
MFD_{const}	1 hour	10 hours	ILB	1 hour
MFD_{sat}	1 hour	3 hours	ILB	1 hour
σ_{URA} [m]	IAURA (note 3)	9	6	7
σ_{URE}[m]	Nominal URA (note 3)	8	4	7
Fault Threshold [m]	4.42 x IURA (10.6)	35	25	31

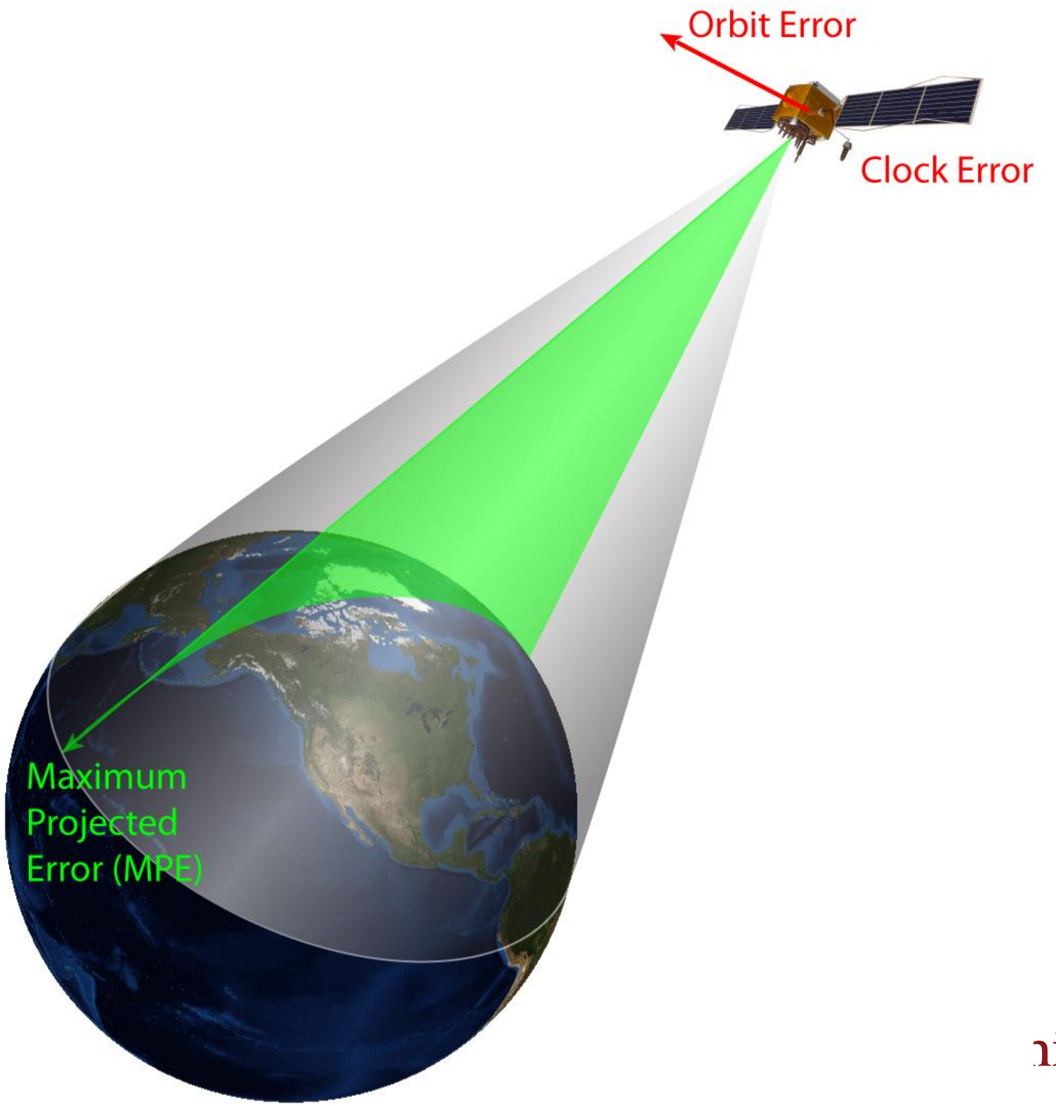
Detremination of Signal-in-Space Errors



Maximum Projected Error (MPE)

- Analytic calculation given clock and orbit error

- MPE will lie in plane containing orbit error and center of Earth



GPS Observations

SV healthy with valid comparison

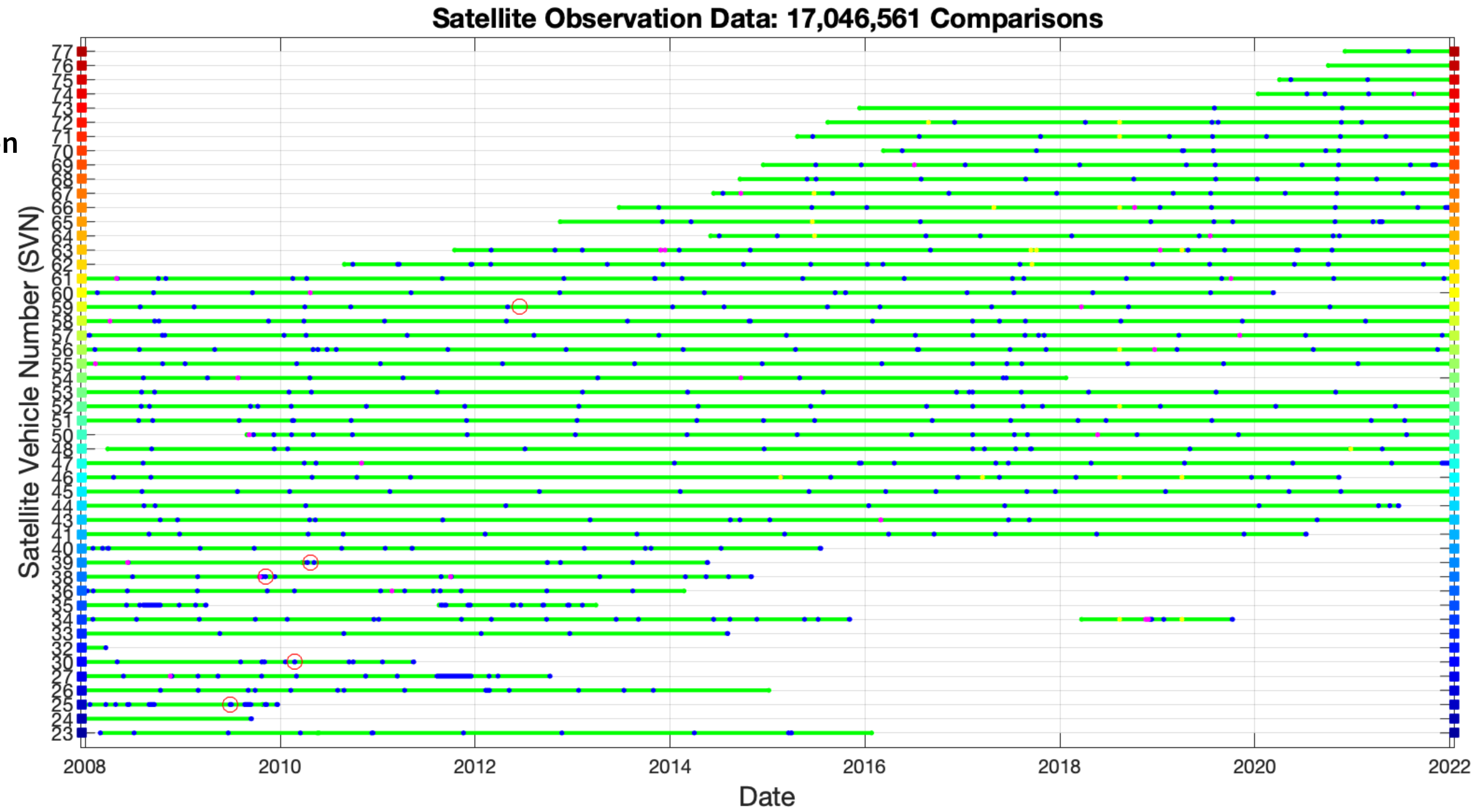
SV unhealthy

Satellite Fault

Five observed faults over last 14 years

Always only one fault at a time

Mean Fault Duration (*MFD*) = ~21 minutes



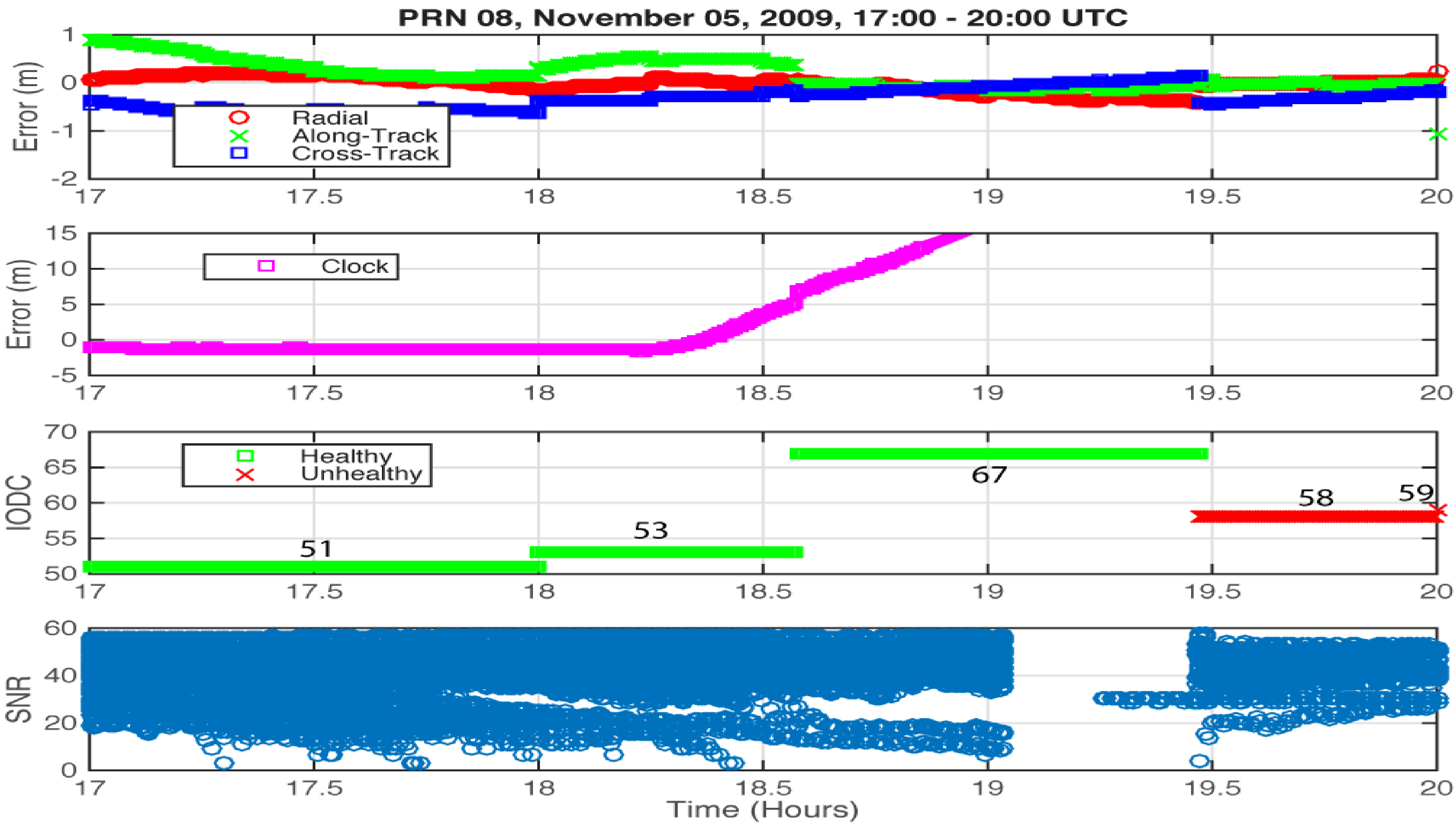
Missing truth data

Missing ephemeris data

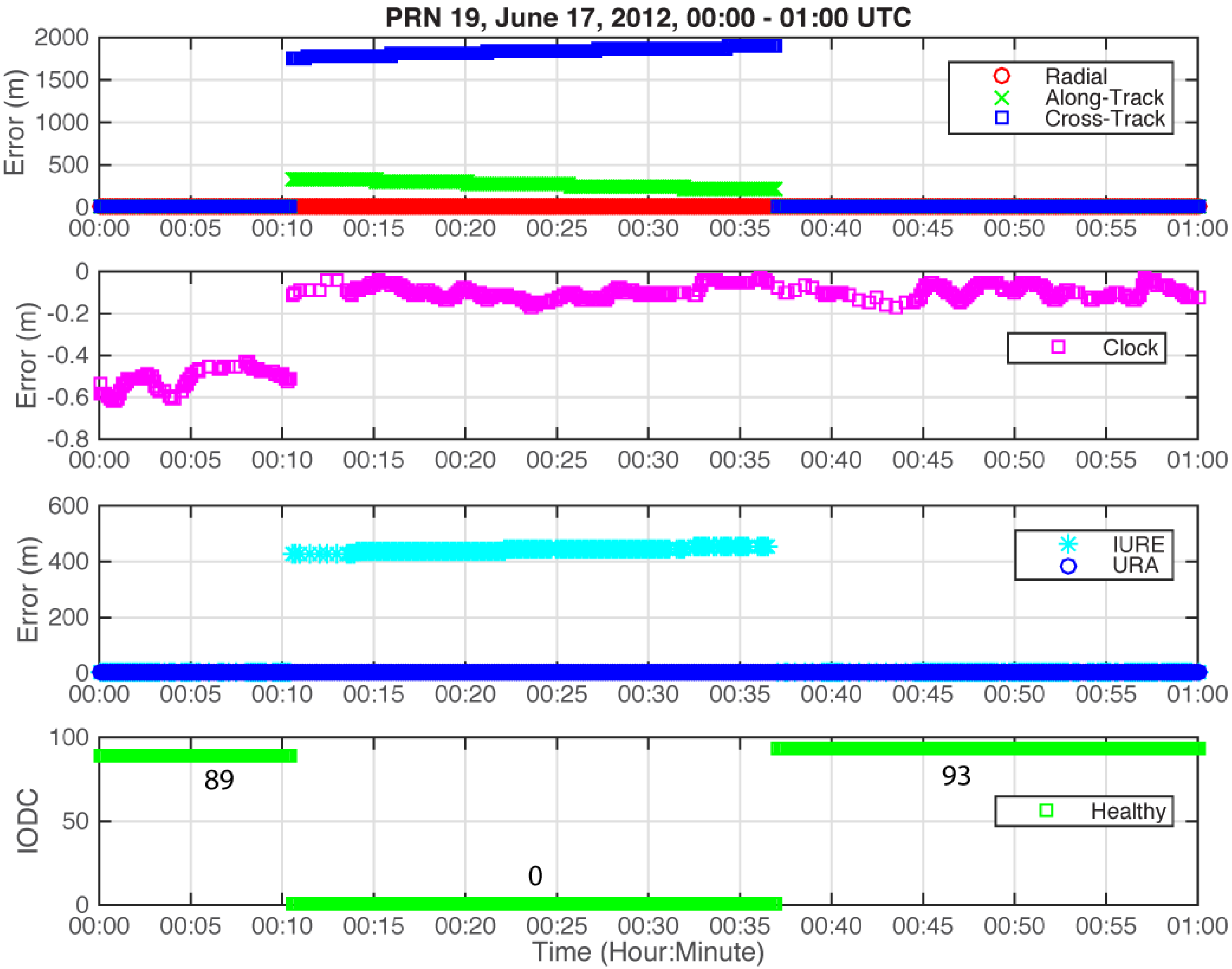
Observed GPS Fault List Since January 2008

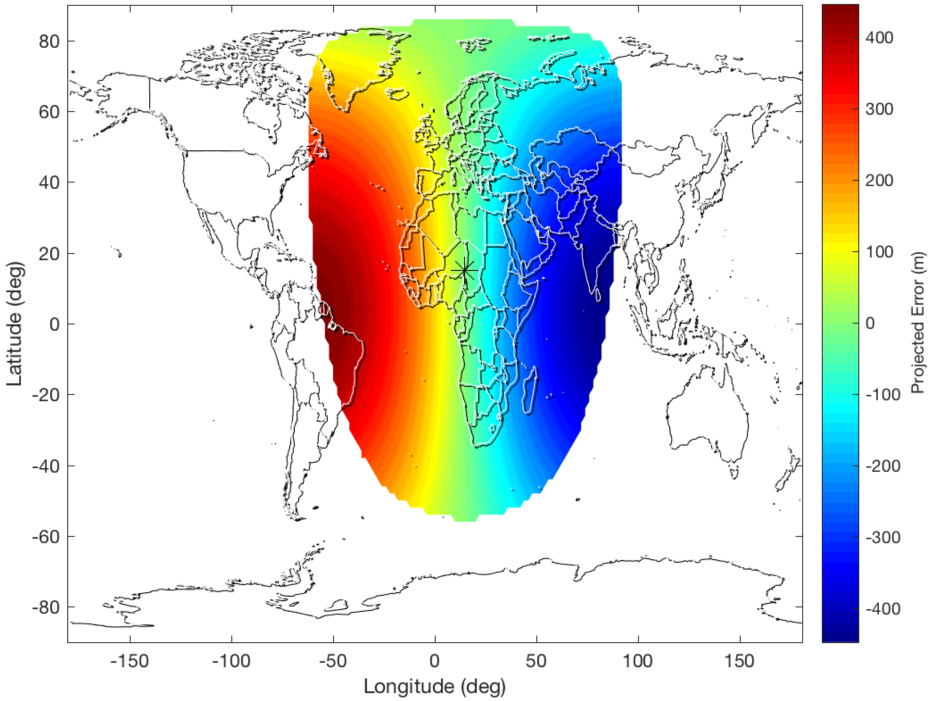
PRN	SVN	Date	UTC Time
25	25	June 26, 2009	09:05:00 –09:45:30
8	38	November 5, 2009	18:44:45 – 19:02:00
30	30	February 22, 2010	20:45:30 – 20:52:00
9	39	April 25, 2010	19:40:30 – 19:55:30
19	59	June 17, 2012	00:10:30 – 00:36:30
12	58	October 2, 2022	14:32 – 15:57:30

Fault on GPS PRN 8, November 5, 2009

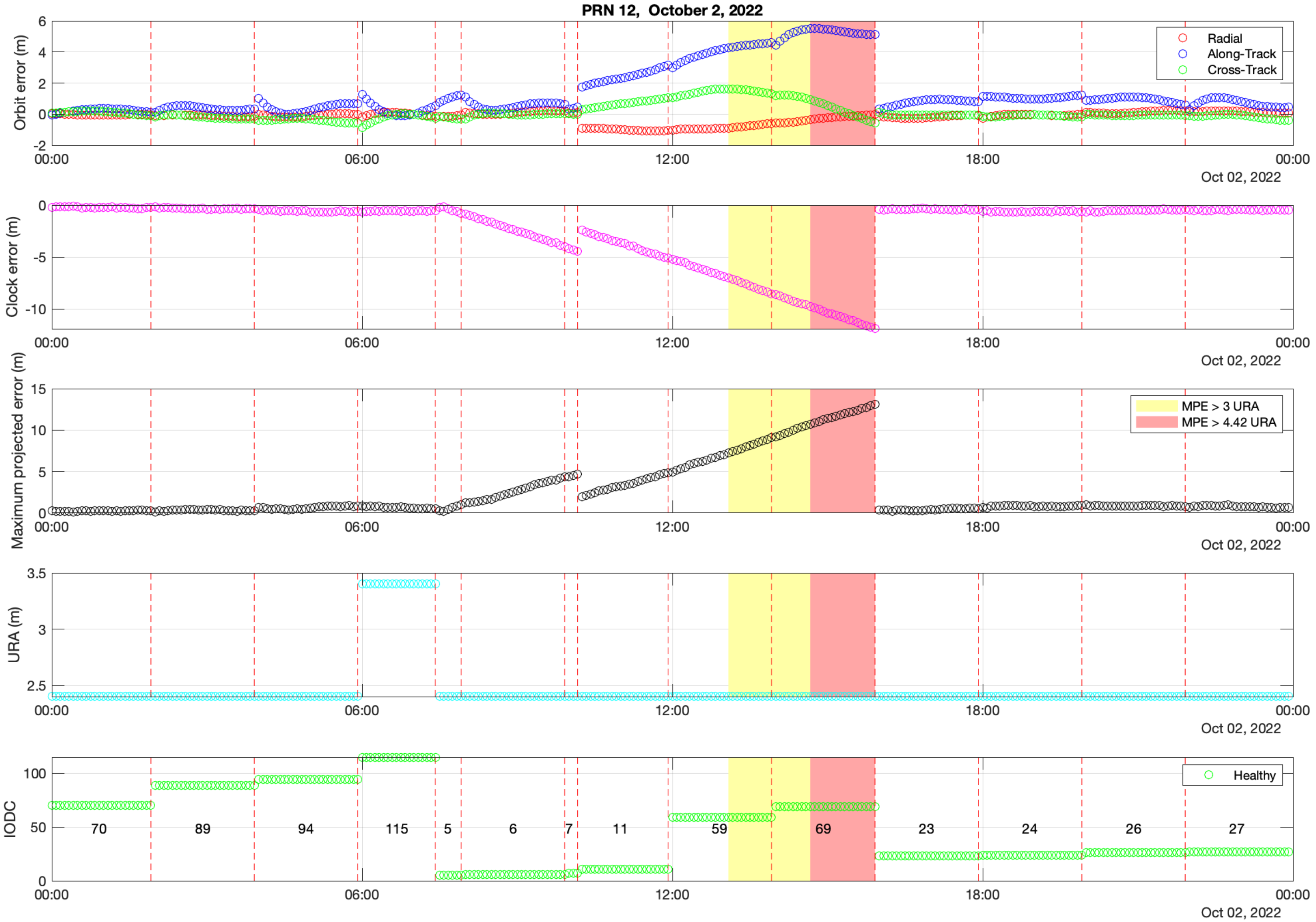


Fault on GPS PRN 19, June 17, 2012



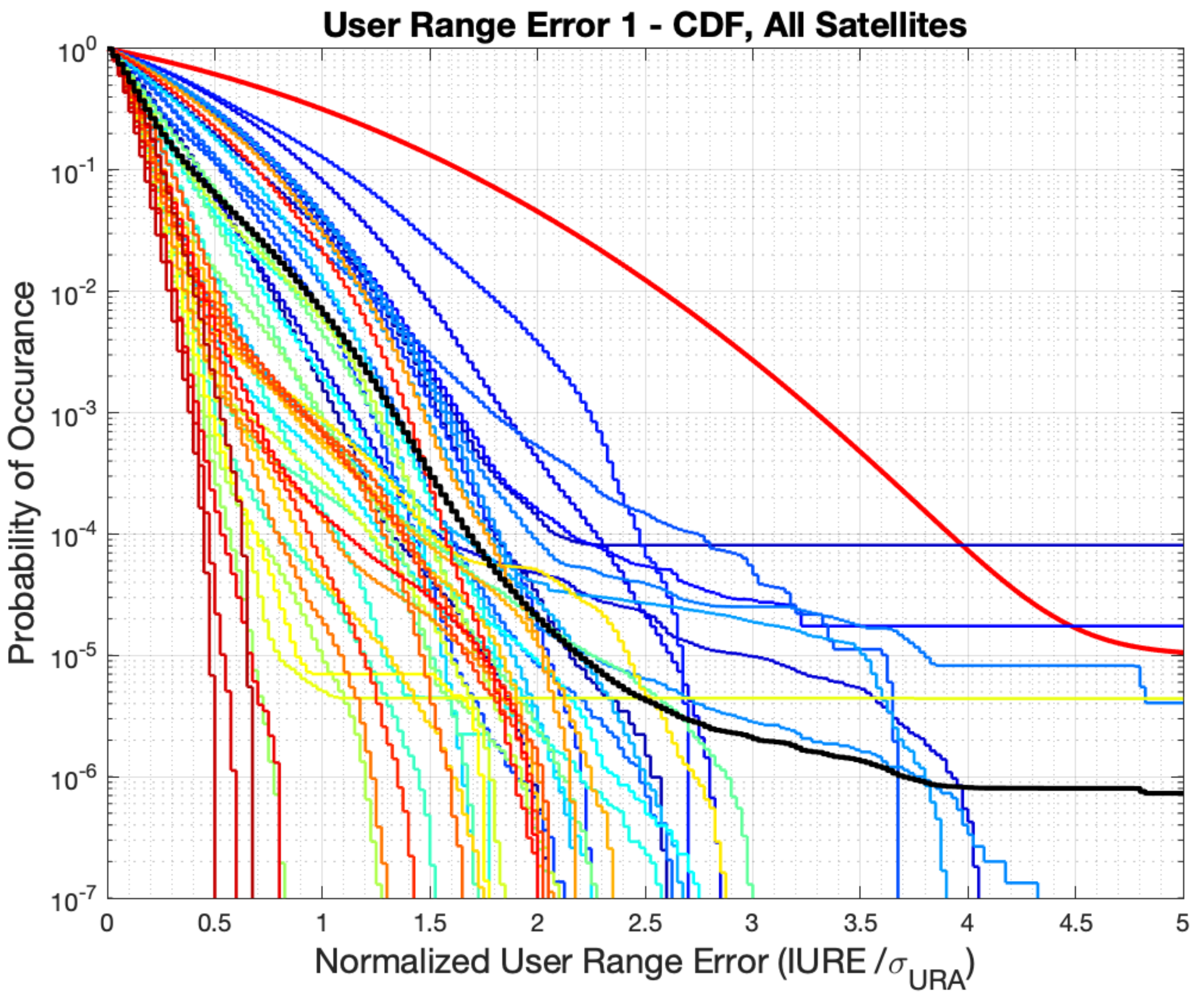


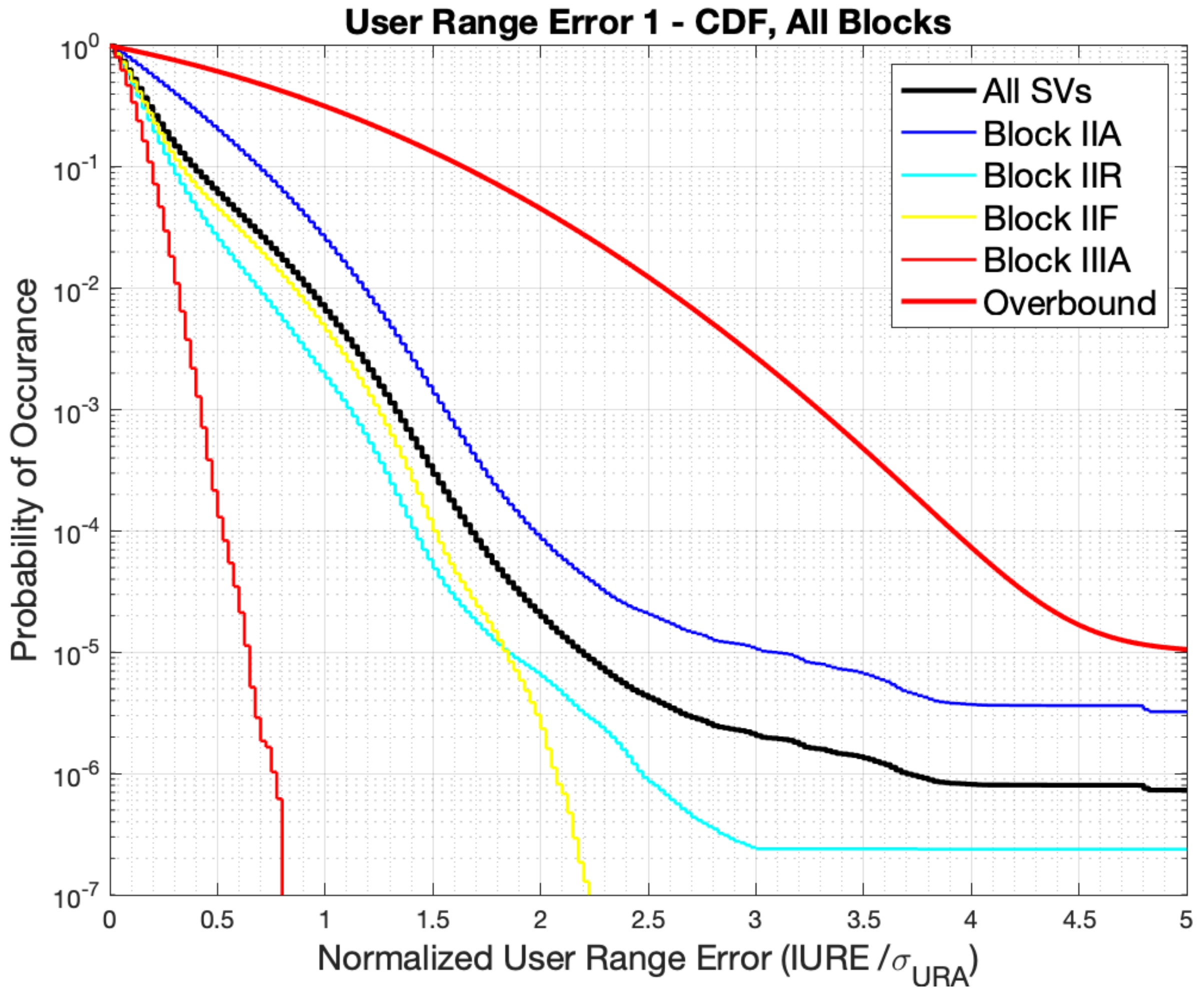
Fault on GPS PRN 12, October 2, 2022



Stanford University

Nominal GPS Error Distributions





Poisson Distribution For Fault Onset

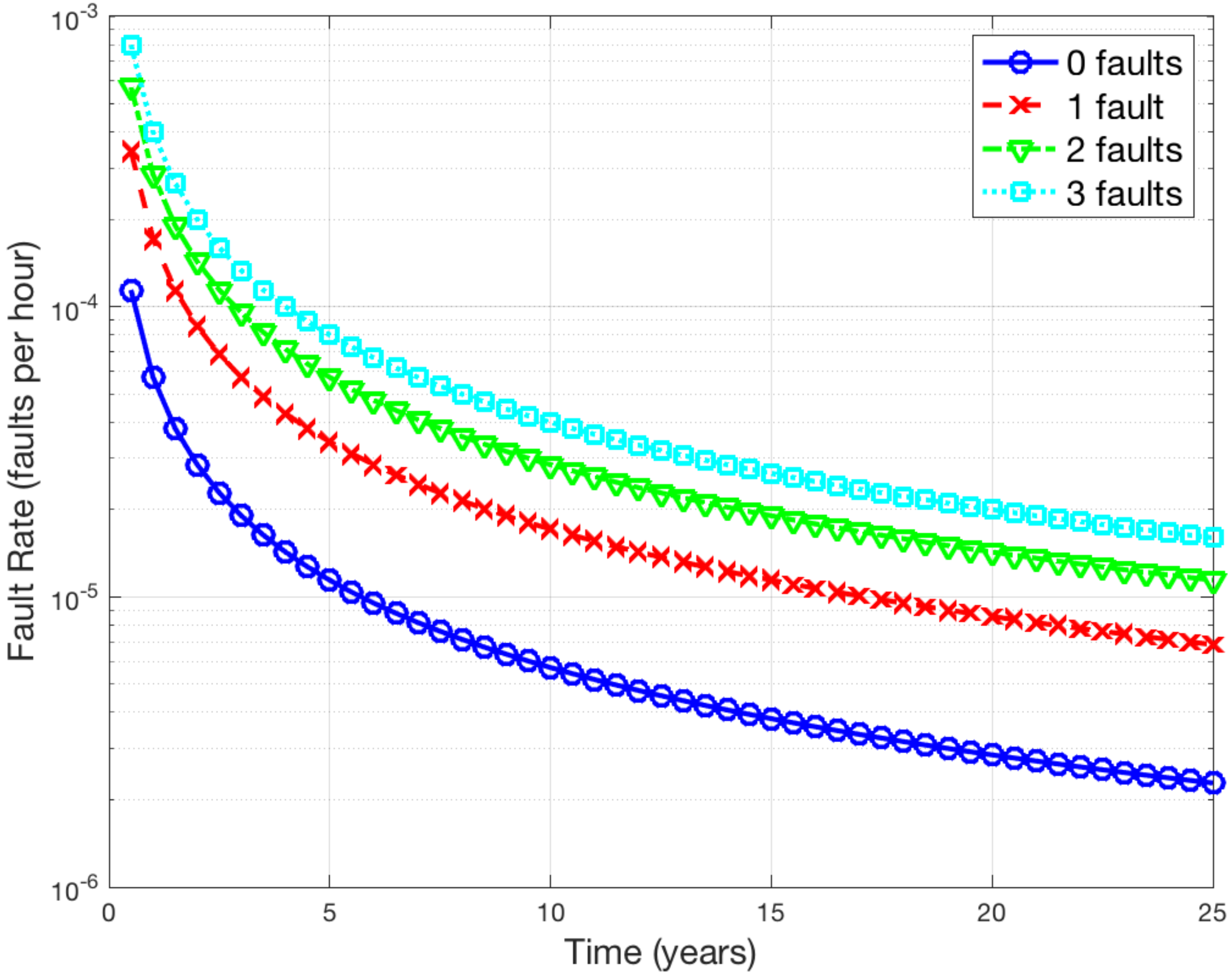
- The probability of a fault occurring within a time interval is proportional to the length of that time interval,
- A fault occurring in one time interval does not affect the probability of it occurring in other time intervals (when the SV is set healthy), and
- The probability of a fault occurring does not change over time.

$$P(k|R) = \frac{(R\,T)^k\, e^{-R\,T}}{k!}$$

$$\hat{R} = \left(k + \frac{1}{2}\right)/T$$

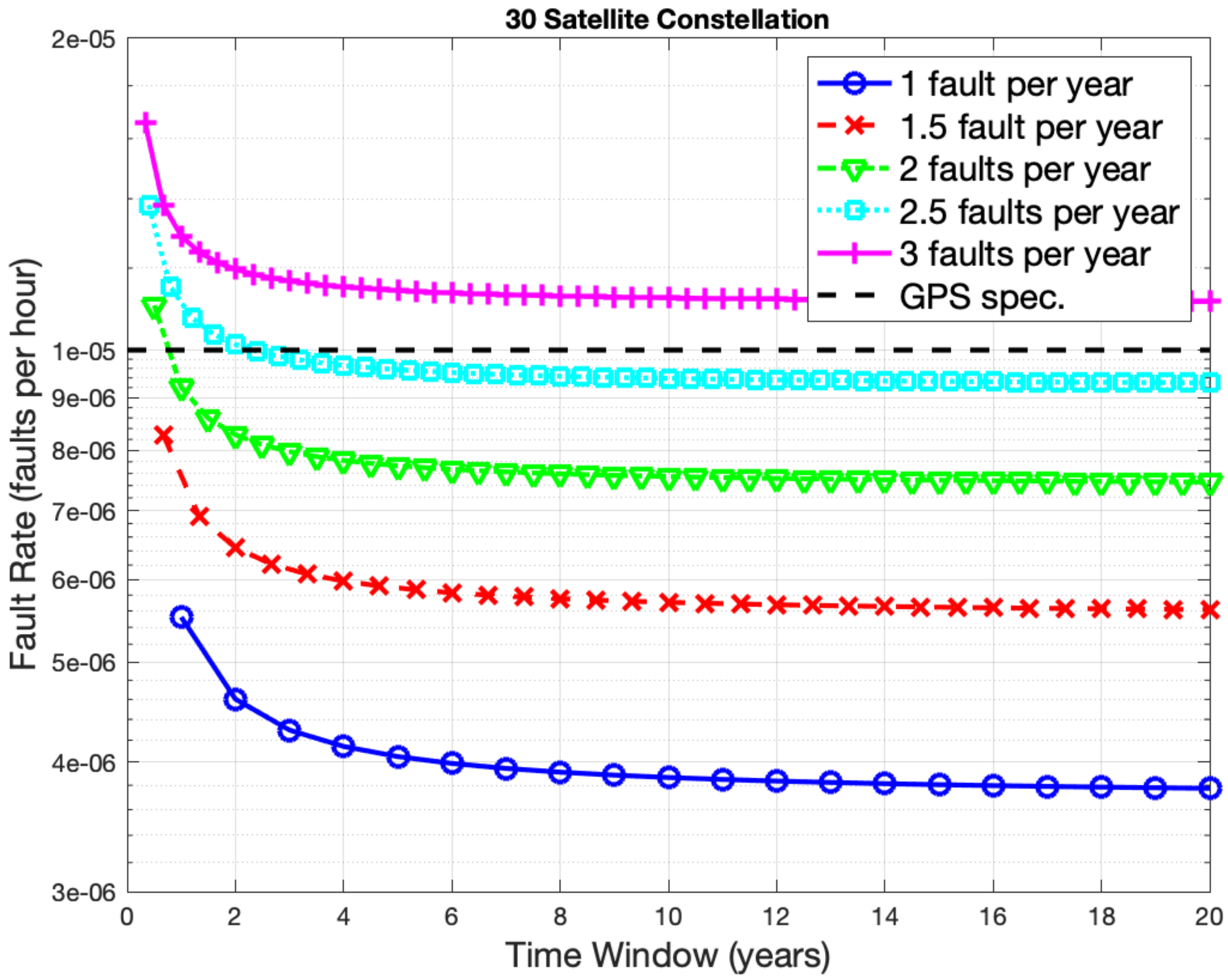
Walter, T., Blanch, J., Gunning, ., Joerger, M., and Pervan, B. "Determination of Fault Probabilities for ARAIM," IEEE Transactions on Aerospace and Electronic Systems, Vol. 55, No. 6, December 2019, DOI 10.1109/TAES.2019.2909727.

Estimated Upper Bound on R_{const}



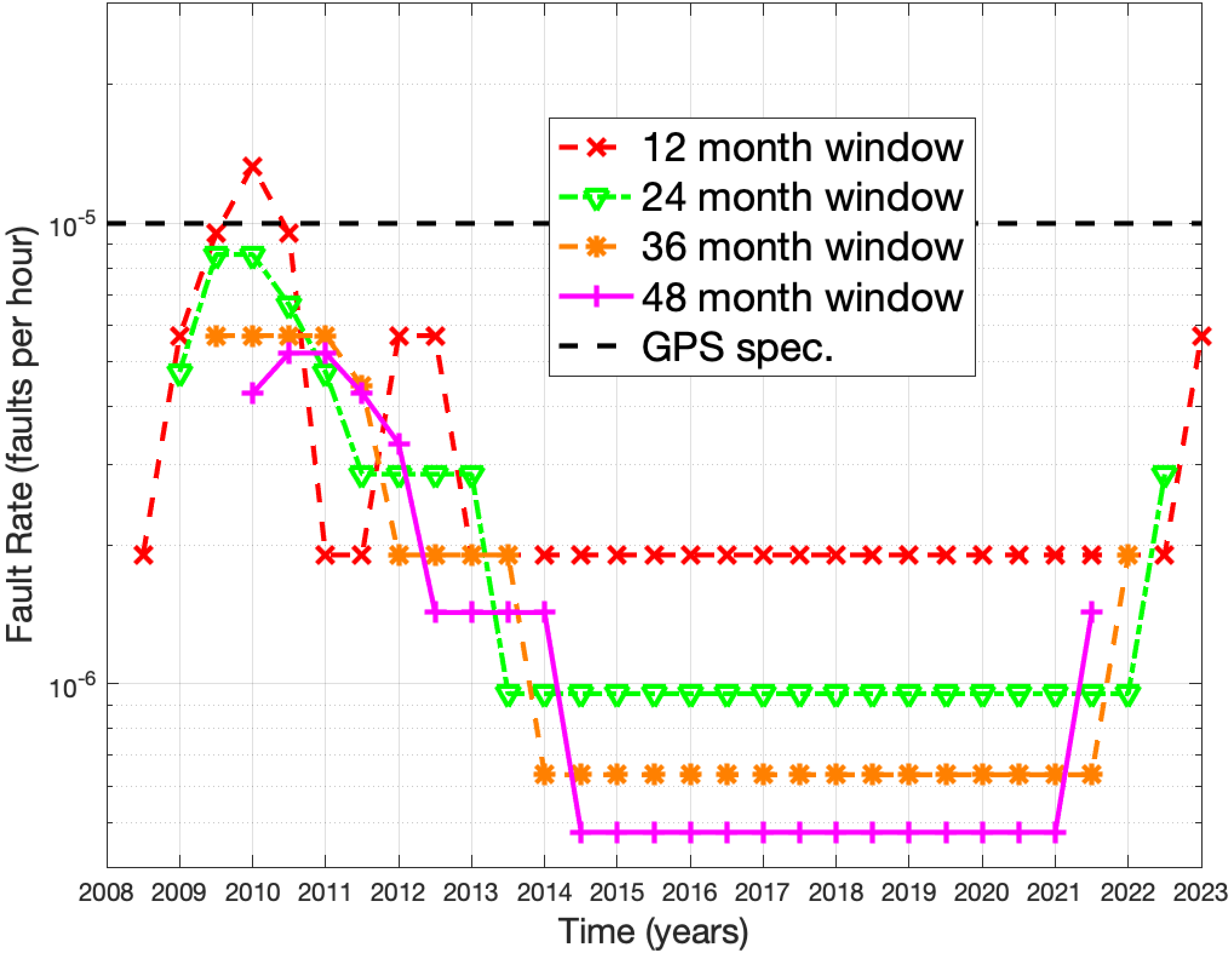
- Cannot bound probabilities much below 10^{-5} using only data validation
- Considering 25 years of GPS service, the smallest bound is ~2.5×10^{-6}/hour
- Must rely on commitments for smaller numbers

Estimated Upper Bound on R_{sat}



- Obtain 31 times more data per hour for GPS
  - Assuming commonality
- More likely to observe faults
- Can obtain better confidence in estimates
- Can observe variations over time

Estimated Upper Bound on GPS R_{sat}



- R_{sat} has improved over time
- Can easily validate committed value of 10^{-5}/hour
- MFD_{sat} is easily bounded by 1 hour
  - ~35 minutes
  - -> $P_{sat} < 10^{-5}$

Probability of Observing *k* Faults within a Time Span

Time Span	*k*	$R_{sat} = 1x10^{-5}$, N = 31
1 Month	0	79.7%
	1	18.1%
	2+	2.2%
1 Quarter	0	50.7%
	1	34.4%
	2	11.7%
	3+	3.2%
1 Year	0	6.6%
	1	17.9%
	2	24.4%
	3	22.1%
	4	15.0%
	5	8.1%
	6+	5.8%

Galileo Observations

SV healthy with valid comparison

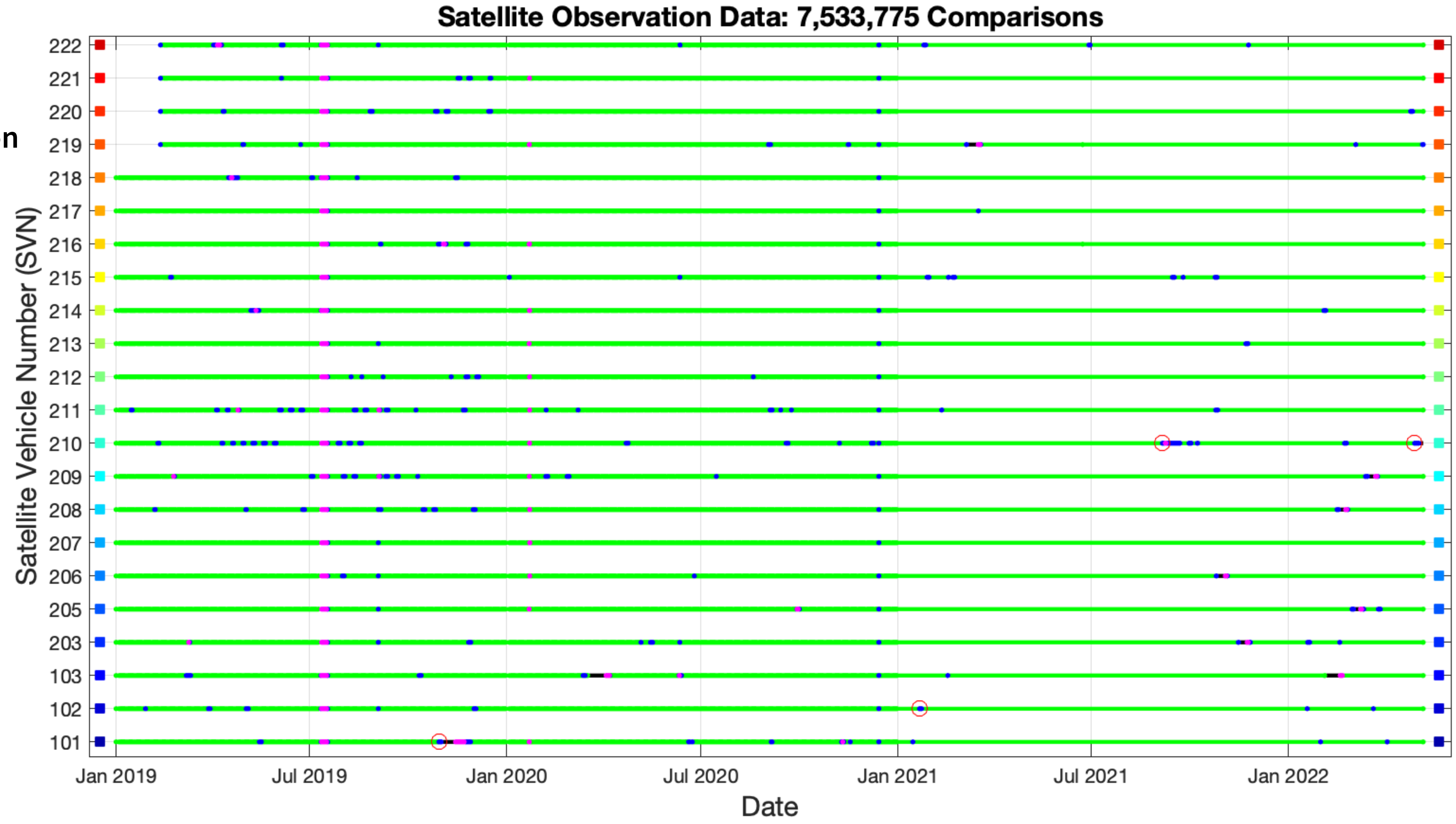
SV unhealthy

Satellite Fault

Four observed faults over last 3.5 years

Always only one fault at a time

Mean Fault Duration (*MFD*) = ~20 minutes



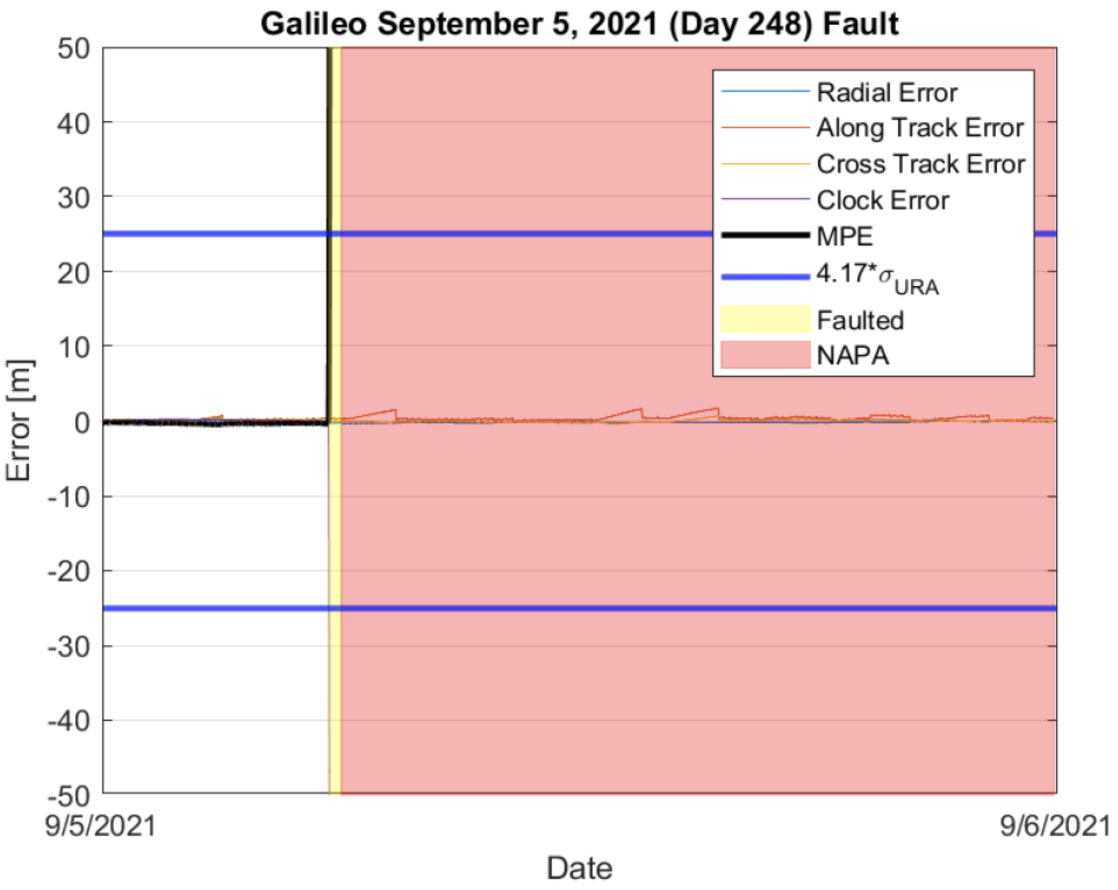
Missing truth data

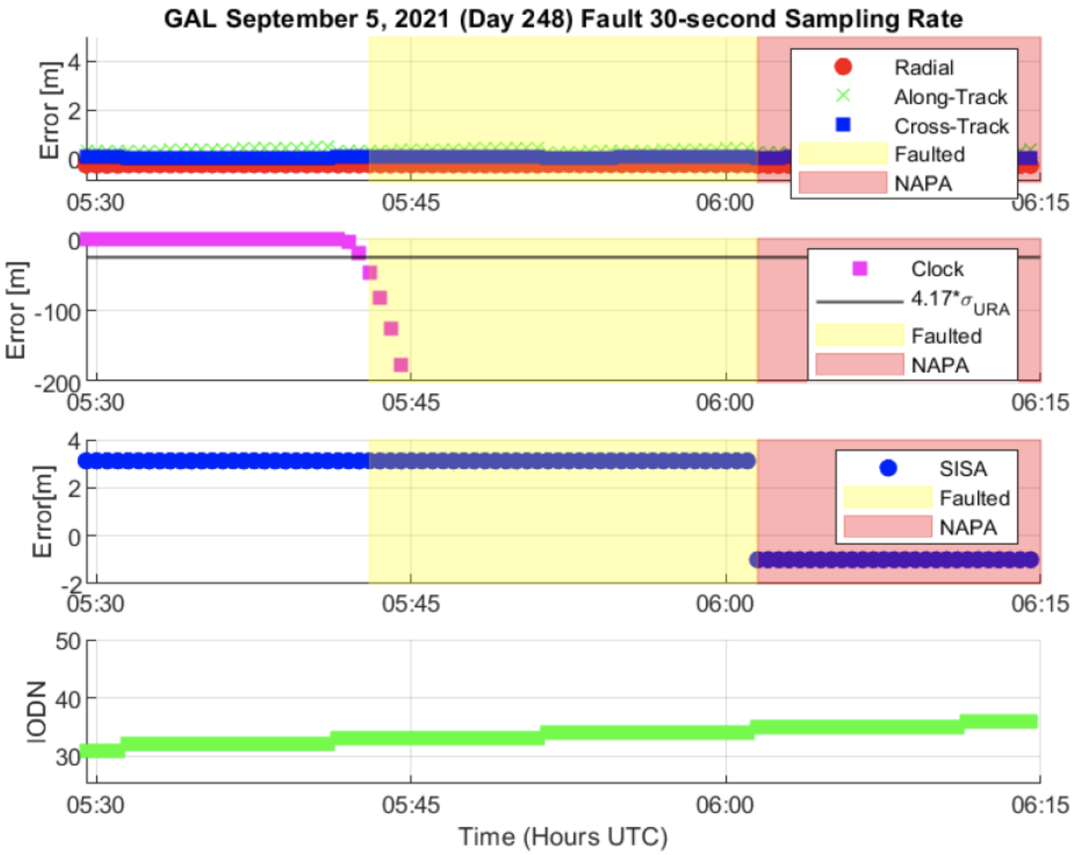
Missing ephemeris data

Observed Galileo Fault List Since January 2019

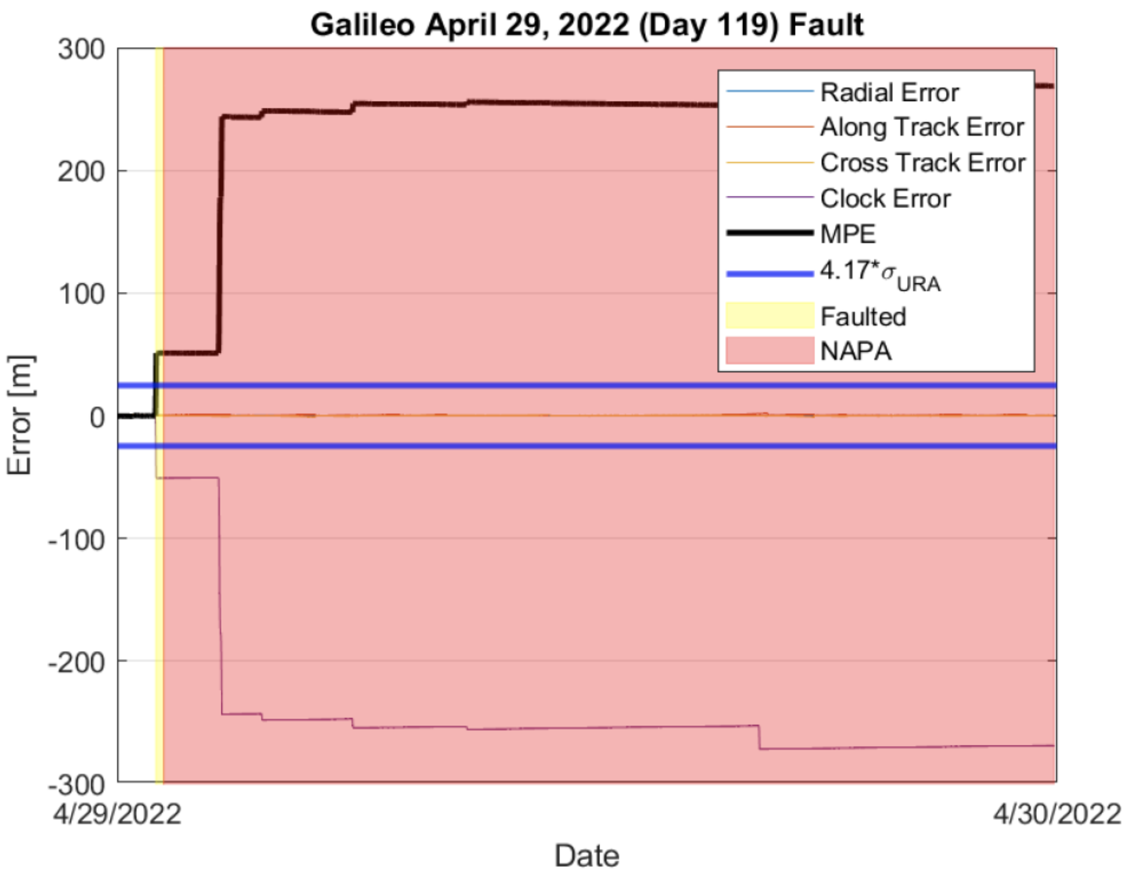
PRN	SVN	Date	UTC Time
11	101	October 29, 2019	~18:15 –18:40
12	102	January 5, 2021	~01:40 –02:00
1	210	September 5, 2021	~05:45 – 06:00
1	210	April 29, 2022	01:00 – 01:10

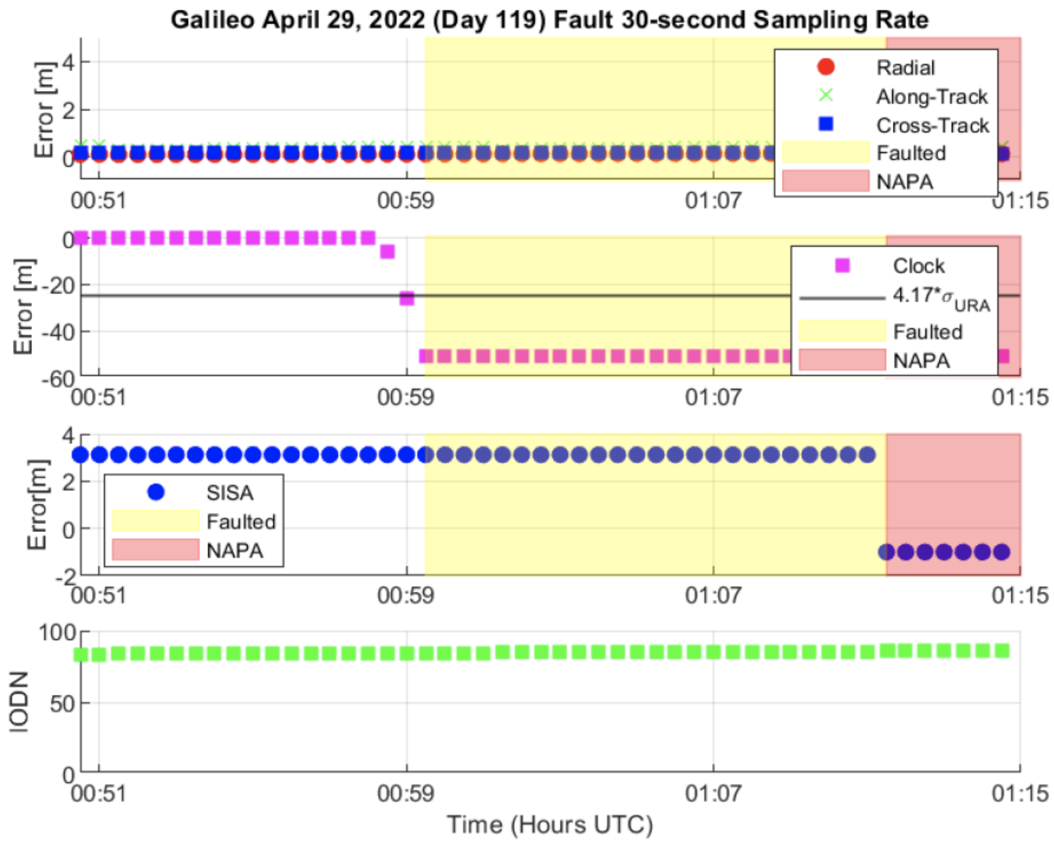
Fault on Galileo PRN 1, September 5, 2021



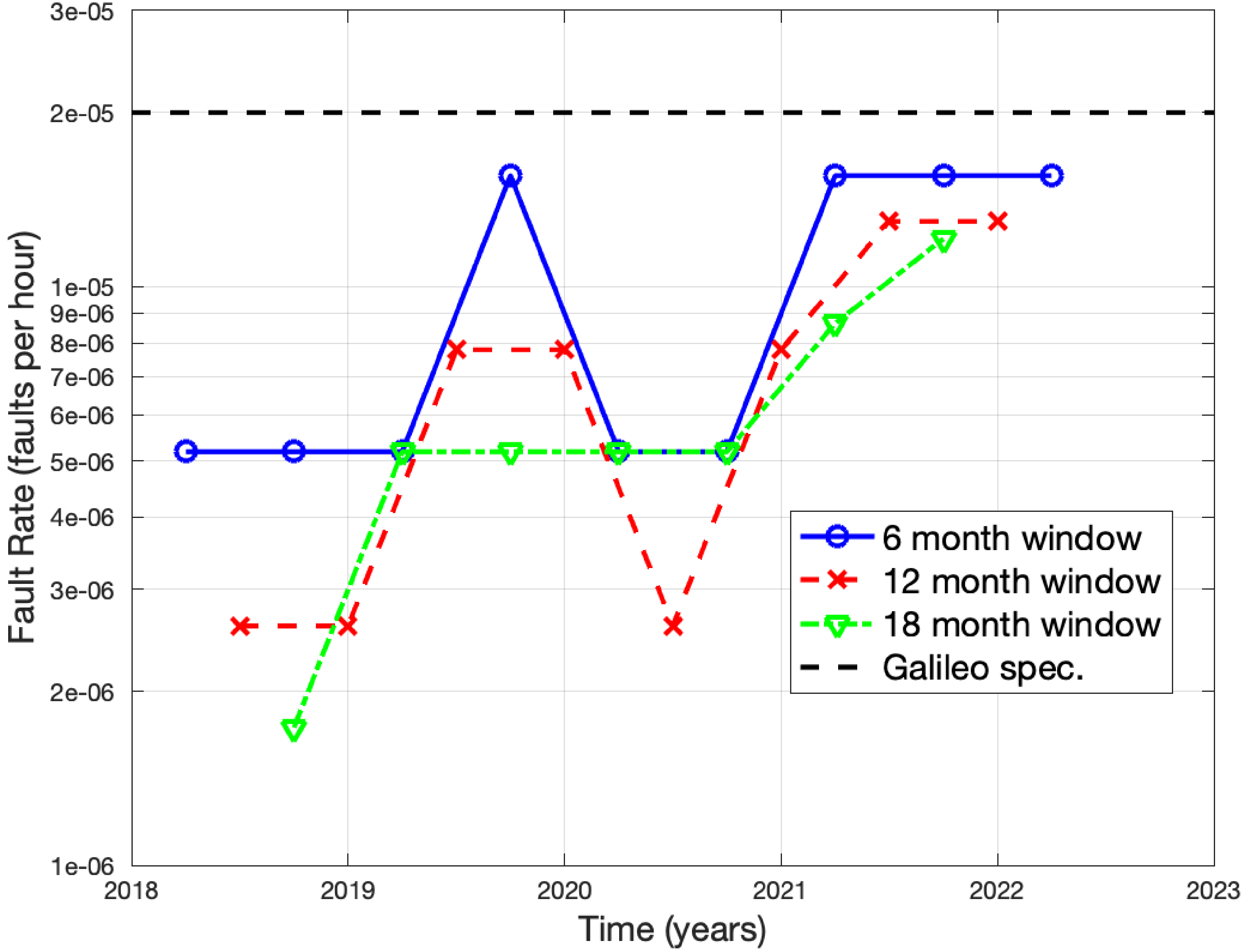


Fault on Galileo PRN 1, April 29, 2022





Estimated Upper Bound on Galileo R_{sat}



- R_{sat} has slightly increased over time
- Can easily validate committed value of $2\text{x}10^{-5}$/hour
- MFD_{sat} is easily bounded by 1.5 hour
  - ~23 minutes
  - -> $P_{sat} < 10^{-5}$

Summary

- Safety-of-life augmentation systems depend on satellites having well characterized nominal behavior coupled with small probabilities of having faults
  - Core constellation integrity commitments are essential to understanding the intended behavior and performance
- Monitoring of the signals is essential to establishing trust in the committed values
- GPS has an excellent track record on meeting its integrity commitments
  - New designs (satellites and control segment) should be monitored to ensure performance standards continue to be met
  - Other constellations will be evaluated against new commitments