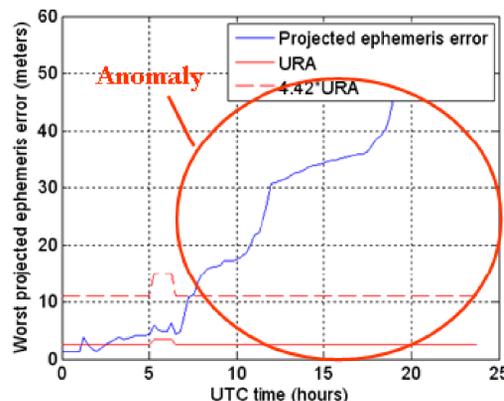


### Motivation

- Basic principle of GPS:  
Broadcast navigation messages  $\Rightarrow$  Real-time satellite positions & clocks  
Pseudorange measurements  $\Rightarrow$  Position fix
- GPS Signal-in-space (SIS) performance is key to positioning accuracy and integrity.
- However, broadcast navigation messages are not error-free.

An SIS anomaly on Aug 17, 2007

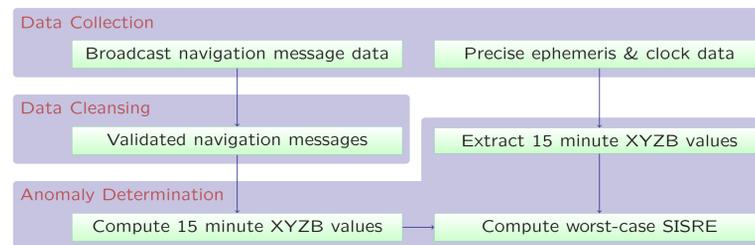
The navigation message was set healthy until 8:00 UTC, but user range errors up to 15 meters were observed.



(Figure courtesy of G. X. Gao, et al. [1])

### Objective and methodology

- Objective: Screen out all potential SIS anomalies in the last decade (6/1/2000–8/31/2010)
- Methodology: Compare broadcast ephemerides & clocks with precise ones [2, 3]

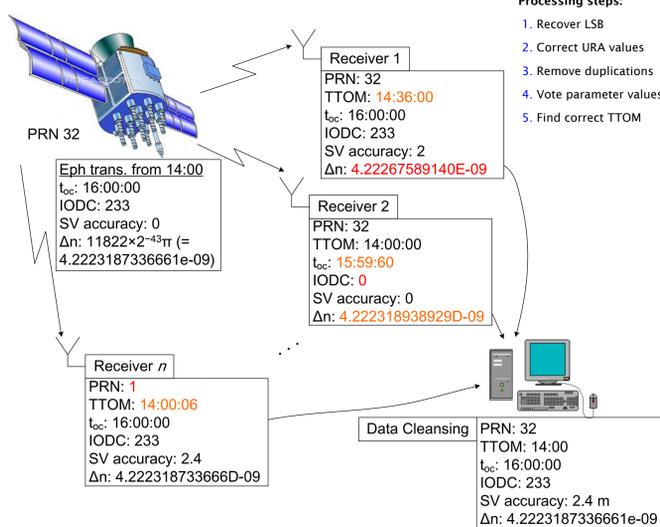


- Highlights:
  - Based on raw log data with possible receiver errors
  - Dedicated algorithm for data cleansing
  - Sophisticated criterion for screening out potential SIS anomalies

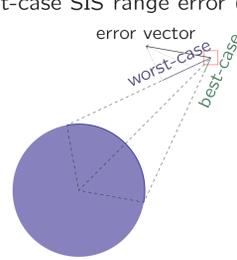
### Data sources

- International GNSS Service (IGS)
  - 350+ volunteer stations
  - Broadcast and precise ephemeris & clock data since 1994
  - 0.34% broadcast data corrupted
  - 1.5% precise data bad or absent
  - Precise data in Center of Mass only
  - Precise data synchronized to either GPS time (before 2/21/2004) or IGS time (after 2/22/2004)
- National Geospatial-Intelligence Agency (NGA)
  - 12+ committed stations
  - Precise ephemeris & clock data since 2006
  - 0.009% precise data bad or absent
  - Precise data in Center of Mass and Antenna Phase Center
  - Precise data synchronized to either GPS time

### Data cleansing

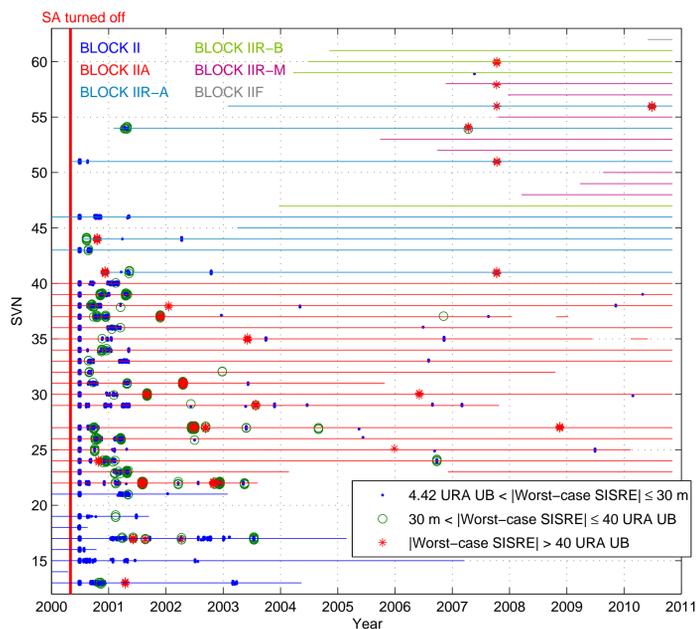


### Anomaly determination

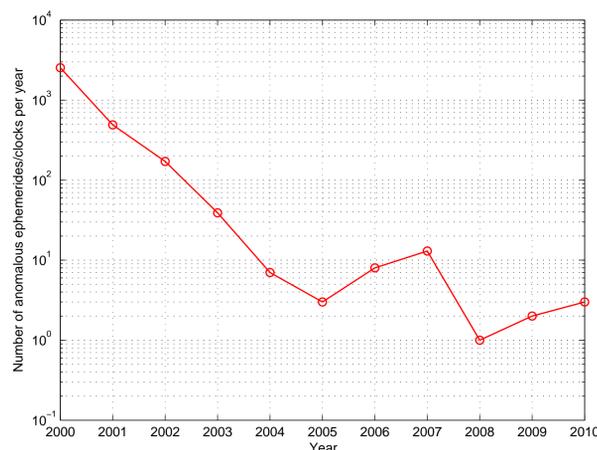
- Propagate broadcast satellite positions & clocks at 15-minute intervals that coincide with the precise ones
  - Compute the worst-case SIS range error (SISRE)
- 
- Criteria for a potential SIS anomaly:
    - Broadcast navigation message is healthy and within 4 hours
    - Precise ephemeris & clock are available
    - Worst-case SISRE > 4.42 × user range accuracy (URA) upper bound (UB) [4]

### Results

- Diagram of potential SIS anomalies 6/1/2000–8/31/2010



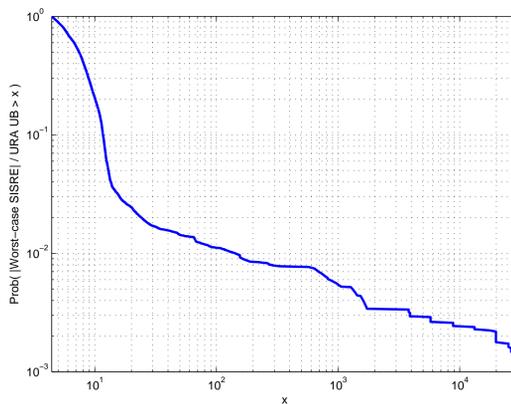
- Number of potential SIS anomalies per year



- List of potential SIS anomalies 1/1/2004–8/31/2010

Date/time	PRN	Duration	Anomaly	URA UB (m)	References
2004-05-03 11:00	08	30 minutes	clock -30.8 m	3.4	IGS
2004-06-14 11:15	29	2.75 hours	ephemeris -10.8 m	2.4	IGS
2004-06-17 11:15	29	1.5 hours	ephemeris 12.5 m	2.4	IGS
2004-07-20 07:15	23	45 minutes	ephemeris 13 m	2.4	IGS
2004-08-29 00:45	27	1 hours	clock 69.5 m	3.4	IGS
2005-05-14 20:15	27	15 minutes	clock 27.6 m	2.4	IGS
2005-06-09 03:45	26	15 minutes	clock -38 m	3.4	IGS
2005-12-25 21:15	25	30 minutes	clock -129 m	2.4	IGS
2006-06-02 20:30	30	30 minutes	clock -1045 m	2.4	NGA
2006-06-27 04:45	06	30 minutes	clock -10.2 m	2.4	IGS, NGA
2006-07-31 22:15	03	1 hour	clock -12.7 m	2.4	IGS, NGA
2006-08-25 12:30	29	1.5 hours	clock -11.6 m	2.4	IGS, NGA
2006-09-22 19:45	24	2.75 hours	ephemeris 41.2 m	2.4	IGS, NGA
2006-11-07 01:45	05	3.75 hours	clock -30.7 m	2.4	IGS, NGA
2007-03-01 14:45	29	2.5 hours	clock -42.3 m	2.4	IGS, NGA
2007-04-10 16:00	18	1.75 hours	ephemeris 688 m	2.4	IGS, NGA
2007-04-22 10:30	25	45 minutes	clock -29.4 m	6.85	NGA
2007-05-20 03:45	19	15 minutes	ephemeris -13.3 m	2.4	IGS, NGA
2007-08-17 07:30	07	30 minutes	clock -14.3 m	2.4	IGS, NGA
2007-10-08 09:45	12	2.25 hours	clock -86 km	2.4	NGA
2007-10-08 23:00	14	1.5 hours	clock -112 km	2.4	NGA
2007-10-09 09:45	23	1 hour	clock 27 km	6.85	NGA
2007-10-09 13:15	16	15 minutes	clock -18 km	4.85	IGS, NGA
2007-10-10 08:45	20	1.25 hours	clock 48 km	2.4	IGS, NGA
2008-11-14 05:45	27	3.75 hours	clock -70 km	2.4	NGA
2009-06-26 09:30	25	45 minutes	clock -22.3 m	2.4	NGA
2009-11-05 18:45	08	30 minutes	clock -18.5 m	2.4	IGS
2010-02-22 21:00	30	30 minutes	clock -42.9 m	3.4	NGA
2010-04-25 19:45	09	15 minutes	ephemeris 11 m	2.4	IGS, NGA
2010-06-24 18:30	16	2 hours	clock 374 m	2.4	NGA

- Cumulative distribution of anomalous worst-case SISRE



### Summary

- Data mining
  - 400,000,000+ broadcast navigation messages (1,360,000+ of them corrupted)
  - 300+ GB data files
- Impressive results
  - 3,200+ potential SIS anomalies found
  - 30,000+ false anomalies due to corrupted data excluded
  - Never did two anomalies or more happen simultaneously in last 6 years
  - 10% anomalies: worst-case SISRE > 10 × URA UB
  - 1% anomalies: worst-case SISRE > 100 × URA UB
- GPS SIS performance improving over last 10 years

### Acknowledgment

This research is supported by the Federal Aviation Administration under Cooperative Agreement 08-G-007.

### References

- G. X. Gao, H. Tang, J. Blanch, J. Lee, T. Walter, and P. Enge, "Methodology and case studies of signal-in-space error calculation top-down meets bottom-up," *ION GNSS 2009*, Sep. 2009
- L. Heng, G. X. Gao, T. Walter, and P. Enge, "GPS ephemeris error screening and results for 2006–2009," *ION ITM 2010*, Jan. 2010
- L. Heng, G. X. Gao, T. Walter, and P. Enge, "GPS signal-in-space anomalies in the last decade: Data mining of 400,000,000 GPS navigation messages," *ION GNSS 2010*, Sep. 2010
- US DoD, *Global positioning system standard positioning service performance standard*, 4th ed., Sep. 2008