Why Wait? Real-Time GNSS Monitoring for Infrastructure Protection and a Perspective on Galileo vs GPS

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Government sponsorship acknowledged.

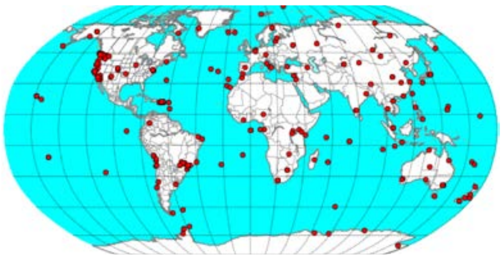
The Global Differential GPS (*GDGPS*) System

Providing mission-critical, real-time services, 24/7, since 2000

Full GNSS capabilities: GPS, GLONASS, BeiDou, Galileo, QZSS, NAVIC

Customer-supported by NASA, industry, DoD

Real-Time Tracking Network (200+ sites)



Measurements →

Triple Hot Redundant Operation Centers

Products, Services →

GNSS Monitoring

Precision Industrial Positioning

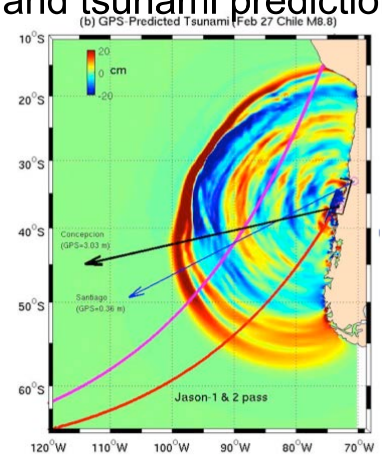
Personal Geolocation

Prototype system and testbed for Next Generation GPS Control Segment (OCX)

Time-critical environmental monitoring services

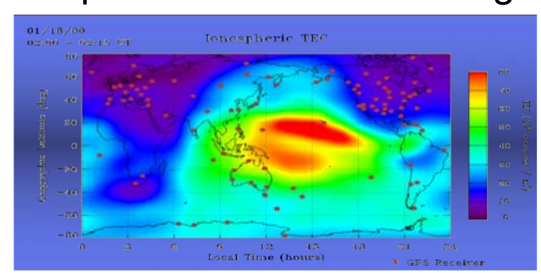
Repeat path interferometry with UAV-SAR

Earthquake monitoring and tsunami prediction



Radio Occultations for weather forecasting

Space weather monitoring



Two Decades of GPS Performance Monitoring for USAF

RMS URE (this snapshot): 0.53 m
Median URE: 0.33 m

Healthy sats only

Mean AOD (Age of Data) 11.5 hours

32 GPS in view (108 sites reporting)

Page generated on Sat Nov 16 18:31:28 2019 (UTC)
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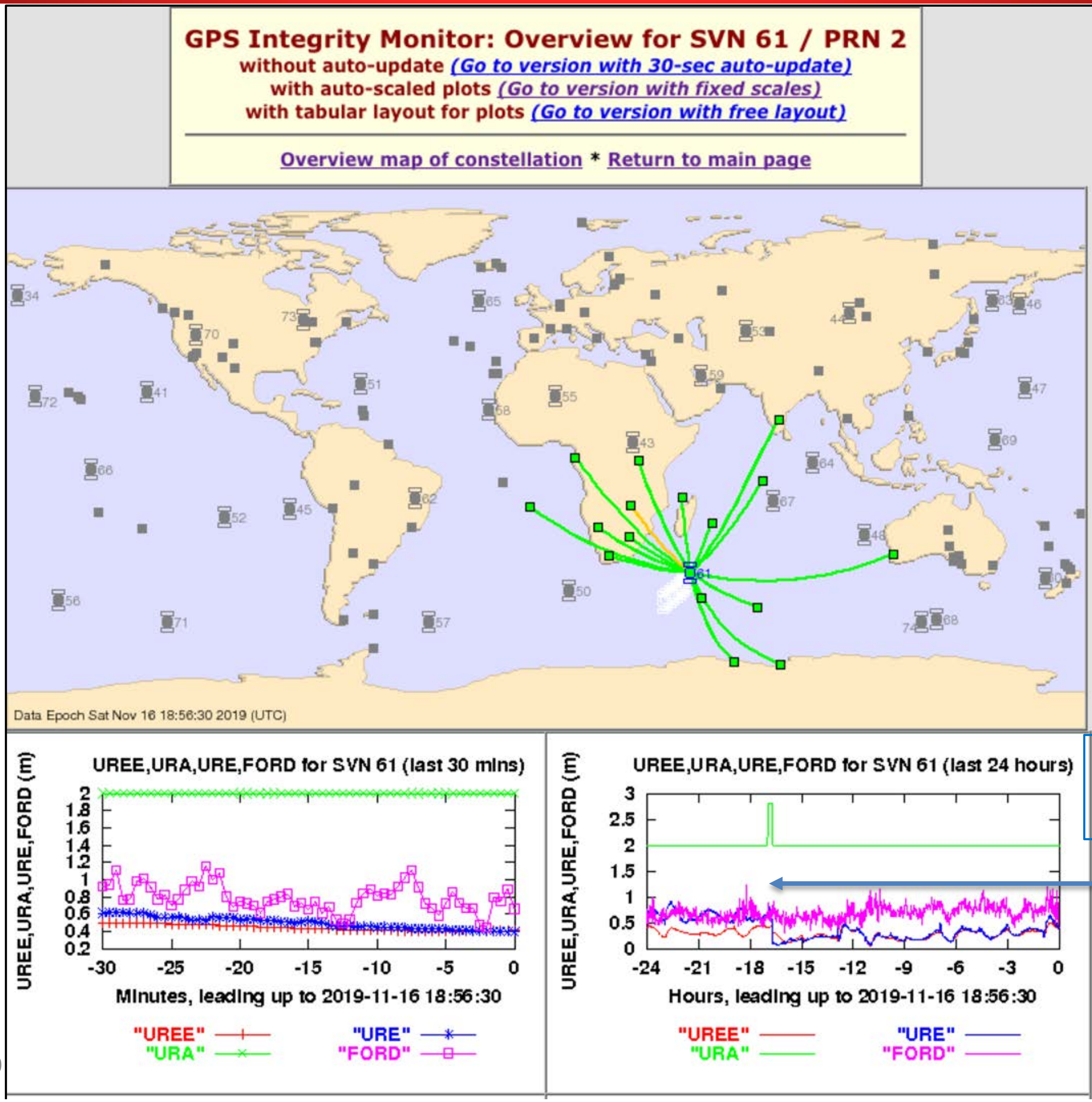
GPS Integrity Monitor: Table sorted by SVN
without auto-update *(Go to version with 30-sec auto-update)*

				Performance metrics				Orbit/Clock error metrics					UTC Model		Link Statistics							
SVN (?)	PRN (?)	Orbit (?)	Block (?)	URE (plot,?)	FORD (plot,?)	URA (plot,?)	URE/URA (plot,?)	UREE (plot,?)	CLK (plot,?)	RSS (plot,?)	RAC (plot,?)	SIGMA (plot,?)	dUTC (plot,?)	dtRef (plot,?)	Total (plot,?)	Good (plot,?)	Bad (plot,?)	Missing (plot,?)	BCE (plot,?)	AOD (plot,?)	Health (plot,?)	SVN (?)
34	18	D-6	IIA	-	-	-	-	-	-	-	plot	-	-	-	30	24	0	6	30	3.3	63	34
41	14	F-1	IIR	0.12	0.86	2.00	0.06	0.06	0.08	0.43	plot	0.00	-0.297	-46.4	22	22	0	0	21	7.0	0	41
43	13	F-2	IIR	0.11	1.05	2.00	0.06	0.10	0.04	0.74	plot	0.00	-0.144	-22.5	43	43	0	0	24	22.5	0	43
44	28	B-3	IIR	1.55	0.84	4.00	0.39	0.11	-1.44	0.28	plot	0.00	-0.297	-46.4	39	39	0	0	27	20.3	0	44
45	21	D-3	IIR	0.17	0.96	2.00	0.09	0.17	-0.09	1.19	plot	0.00	-0.297	-46.4	24	24	0	0	20	17.8	0	45
46	11	D-2	IIR	1.05	1.78	2.00	0.53	0.26	0.81	0.87	plot	0.00	-0.297	-46.4	29	27	0	2	28	11.5	0	46
47	22	E-2	IIR	0.41	0.96	2.00	0.20	0.07	-0.38	0.46	plot	0.00	-0.297	-46.4	31	30	0	1	23	19.3	0	47
48	7	A-4	IIR-M	0.04	0.80	2.00	0.02	0.21	-0.24	0.30	plot	0.00	-0.148	-46.4	26	26	0	0	22	0.8	0	48
50	5	E-3	IIR-M	0.43	0.76	2.00	0.22	0.18	-0.27	0.62	plot	0.01	-0.297	-46.4	24	23	0	1	13	8.3	0	50
51	20	E-7	IIR	0.34	0.86	2.00	0.17	0.10	-0.26	0.49	plot	0.00	-0.148	-46.4	43	43	0	0	24	3.5	0	51
52	31	A-2	IIR-M	0.86	0.51	2.00	0.43	0.21	0.67	0.75	plot	0.00	-0.297	-46.4	13	13	0	0	17	11.3	0	52
53	17	C-4	IIR-M	0.45	0.51	2.00	0.22	0.27	0.18	0.47	plot	0.00	-0.297	-46.4	42	41	0	1	31	7.5	0	53
55	15	F-2	IIR-M	0.33	0.49	2.00	0.17	0.24	0.17	1.65	plot	0.00	-0.297	-46.4	42	42	0	0	23	14.3	0	55
56	16	B-1	IIR	0.25	0.76	2.00	0.12	0.13	-0.13	0.69	plot	0.00	-0.297	-46.4	20	19	0	1	11	8.8	0	56
57	29	C-1	IIR-M	0.65	0.86	2.00	0.33	0.21	-0.67	1.47	plot	0.01	-0.297	-46.4	16	16	0	0	9	17.5	0	57
58	12	B-4	IIR-M	0.09	1.02	2.00	0.05	0.28	0.24	0.68	plot	0.00	-0.144	-22.5	41	41	0	0	23	22.3	0	58
59	19	C-3	IIR	0.09	0.88	2.00	0.05	0.22	-0.30	0.37	plot	0.00	-0.297	-46.4	36	36	0	0	25	9.5	0	59
60	23	F-4	IIR	0.28	0.47	2.00	0.14	0.14	0.20	1.01	plot	0.00	-0.297	-46.4	21	21	0	0	6	17.8	0	60
61	2	D-1	IIR	0.56	0.82	2.00	0.28	0.49	-0.11	2.91	plot	0.01	-0.297	-46.4	20	19	0	1	11	17.0	0	61
62	25	B-2	IIF	0.18	0.43	2.00	0.09	0.21	-0.06	1.22	plot	0.01	-0.297	-46.4	19	19	0	0	12	19.8	0	62
63	1	D-2	IIF	0.07	0.39	2.00	0.04	0.15	-0.21	0.29	plot	0.00	-0.297	-46.4	28	26	0	2	28	6.0	0	63
64	30	A-3	IIF	0.35	0.71	2.00	0.18	0.17	0.18	0.31	plot	0.00	-0.297	-46.4	28	27	0	1	29	14.0	0	64
65	24	A-1	IIF	1.12	1.08	2.00	0.56	0.26	0.89	0.95	plot	0.00	-0.148	-46.4	48	48	0	0	30	2.3	0	65
66	27	C-2	IIF	0.33	0.71	2.00	0.16	0.09	-0.24	0.20	plot	0.00	-0.148	-46.4	24	24	0	0	23	3.3	0	66
67	6	D-4	IIF	0.55	0.89	2.00	0.27	0.59	-0.05	1.59	plot	0.00	-0.148	-46.4	26	24	0	2	14	0.5	0	67
68	9	F-3	IIF	0.17	0.59	2.00	0.08	0.04	0.14	0.26	plot	0.00	-0.297	-46.4	22	22	0	0	11	4.5	0	68
69	3	E-1	IIF	0.25	0.69	2.00	0.13	0.24	-0.02	1.72	plot	0.00	-0.297	-46.4	27	26	0	1	19	11.3	0	69
70	32	F-1	IIF	0.23	0.69	2.00	0.12	0.16	-0.16	1.14	plot	0.00	-0.297	-46.4	24	23	0	1	25	8.0	0	70
71	26	B-1	IIF	0.42	0.70	2.00	0.21	0.44	0.02	1.28	plot	0.00	-0.297	-46.4	22	22	0	0	10	16.5	0	71
72	8	C-3	IIF	0.46	0.87	2.00	0.23	0.22	0.58	1.17	plot	0.00	-0.297	-46.4	26	26	0	0	28	16.3	0	72
73	10	E-2	IIF	0.15	0.69	2.00	0.07	0.16	0.31	0.18	plot	0.00	-0.297	-46.4	45	44	0	1	31	4.5	0	73
74	4	F-3	IIIA	6.30	6.78	128.00	0.05	5.75	0.55	6.10	plot	0.14	0.777	121.6	21	12	0	9	8	186.8	63	74
SVN	PRN	Orbit	Block	URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	dUTC	dtRef	Total	Good	Bad	Missing	BCE	AOD	Health	SVN

Average observability:
28 sites

Minimum observability:
13 sites

Large Footprint of GPS Satellite Signals and Dense Global Network are key to Resiliency of the GDGPS System



Ephemeris upload 17 hours ago

Galileo Real-Time Performance Monitoring

RMS URE (this snapshot): 0.44 m
Median URE: 0.17 m

Healthy sats only

Mean AOD reported to be < 1 hour

InsideGNSS Sep/Oct 2018

Average observability: 20 sites (this snapshot)

Minimum observability: 5 sites (this snapshot)

23 GAL in view (87 sites reporting)

Page generated on Mon Nov 18 15:43:54 2019 (UTC)
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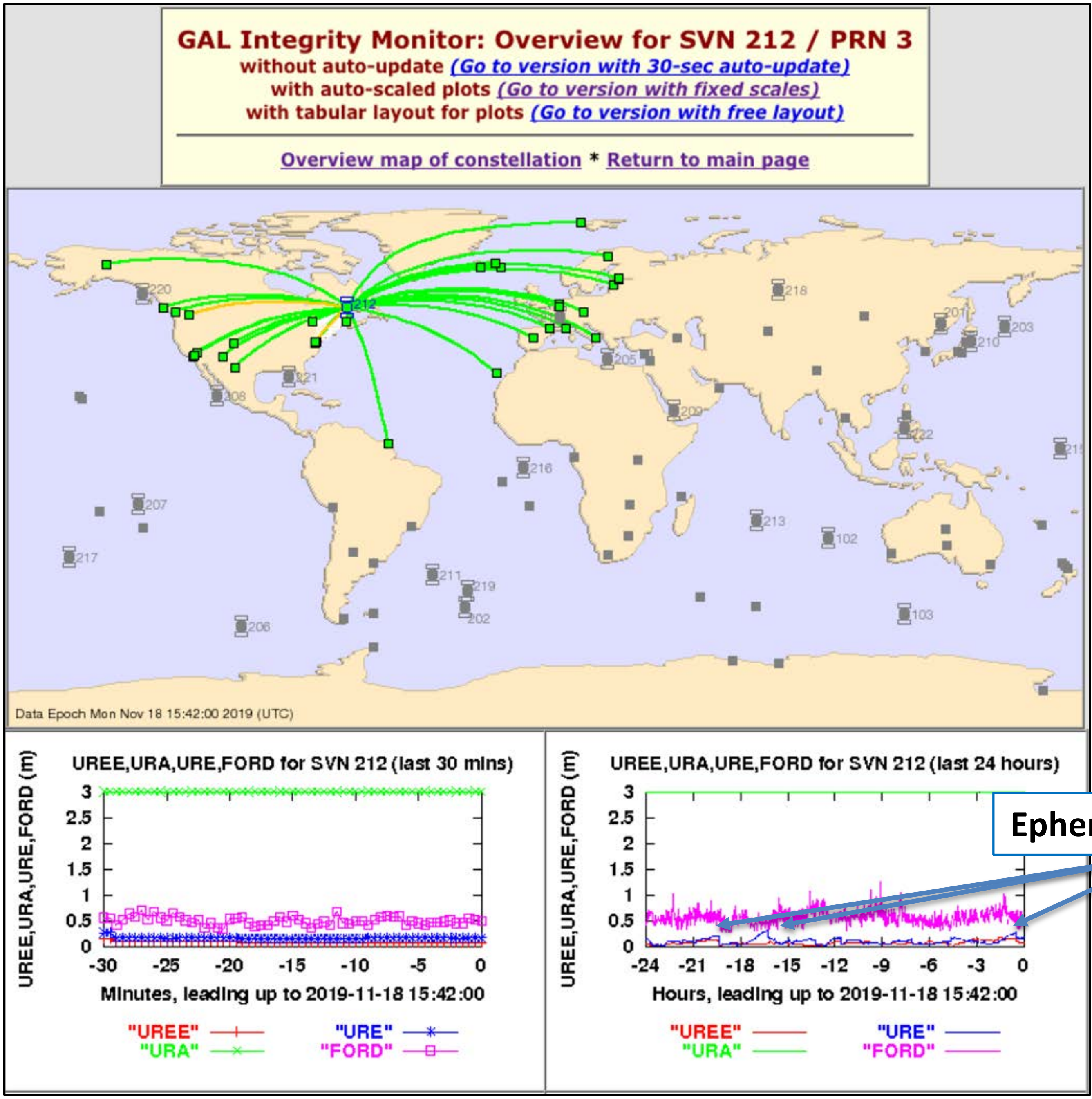
GAL Integrity Monitor: Table sorted by SVN
without auto-update (Go to version with 30-sec auto-update)

			Performance metrics				Orbit/Clock error metrics					Link Statistics							
SVN (?)	PRN (?)	Block (?)	URE (plot,?)	FORD (plot,?)	URA (plot,?)	URE/URA (plot,?)	UREE (plot,?)	CLK (plot,?)	RSS (plot,?)	RAC (plot,?)	SIGMA (plot,?)	Total (plot,?)	Good (plot,?)	Bad (plot,?)	Missing (plot,?)	BCE (plot,?)	AOD (plot,?)	Health (plot,?)	SVN (?)
102	12	IOV	0.73	0.56	3.00	0.24	0.03	0.70	0.09	plot	0.00	20	15	0	5	9	-	0	102
103	19	IOV	0.27	0.47	3.00	0.09	0.19	0.38	0.90	plot	0.00	14	10	0	4	5	-	0	103
201	18	FOCe	0.27	0.42	3.00	0.09	0.24	0.03	0.57	plot	0.00	15	8	0	7	9	-	1	201
202	14	FOCe	0.04	0.36	3.00	0.01	0.06	-0.07	0.24	plot	0.00	26	18	0	8	10	-	1	202
203	26	FOC	0.24	0.59	3.00	0.08	0.35	-0.12	0.45	plot	0.00	18	15	0	3	12	-	0	203
205	24	FOC	1.61	0.46	3.00	0.54	0.13	1.50	0.59	plot	0.00	34	31	0	3	12	-	0	205
206	30	FOC	0.05	0.57	3.00	0.02	0.06	-0.08	0.25	plot	0.00	18	17	0	1	6	-	0	206
207	7	FOC	0.07	0.61	3.00	0.02	0.08	0.06	0.50	plot	0.00	14	14	0	0	10	-	0	207
208	8	FOC	0.17	0.40	3.00	0.06	0.08	-0.08	0.13	plot	0.00	23	21	0	2	14	-	0	208
209	9	FOC	0.08	0.50	3.00	0.03	0.04	-0.09	0.24	plot	0.00	35	33	0	2	13	-	0	209
210	1	FOC	0.08	0.37	3.00	0.03	0.25	-0.18	0.43	plot	0.00	16	14	0	2	10	-	0	210
211	2	FOC	0.20	0.33	3.00	0.07	0.19	-0.01	0.20	plot	0.00	24	21	0	3	11	-	0	211
212	3	FOC	0.15	0.39	3.00	0.05	0.06	0.20	0.29	plot	0.00	36	34	0	2	15	-	0	212
213	4	FOC	0.14	0.52	3.00	0.05	0.11	-0.25	0.17	plot	0.00	20	17	0	3	10	-	0	213
214	5	FOC	0.22	0.34	3.00	0.07	0.04	0.21	0.25	plot	0.00	32	31	0	1	14	-	0	214
215	21	FOC	0.02	0.48	3.00	0.01	0.09	-0.09	0.16	plot	0.00	15	12	0	3	9	-	0	215
216	25	FOC	0.43	0.50	3.00	0.14	0.16	0.27	0.38	plot	0.00	28	28	0	0	13	-	0	216
217	27	FOC	0.07	0.72	3.00	0.02	0.07	-0.12	0.25	plot	0.00	12	5	0	7	5	-	0	217
218	31	FOC	0.20	0.60	3.00	0.07	0.05	0.22	0.32	plot	0.00	32	30	0	2	14	-	0	218
219	36	FOC	0.54	0.31	3.00	0.18	0.06	0.59	0.25	plot	0.00	26	21	0	5	10	-	0	219
220	13	FOC	0.06	0.68	3.00	0.02	0.07	0.01	0.31	plot	0.00	27	25	0	2	18	-	0	220
221	15	FOC	0.19	0.73	3.00	0.06	0.12	0.30	0.30	plot	0.00	24	24	0	0	17	-	0	221
222	33	FOC	0.06	0.41	3.00	0.02	0.14	-0.14	0.44	plot	0.00	14	11	0	3	10	-	0	222
SVN	PRN	Block	URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	Total	Good	Bad	Missing	BCE	AOD	Health	SVN

Galileo is Well Observed by the GDGPS System; Multiple Ephemeris Uploads Hardly Noticeable



Similar GDGPS Monitors for GLONASS and BeiDou

35 BDS in view (69 sites reporting)

Page generated on Sat Nov 16 19:40:24 2019 (UTC)
Data Epoch: 24 seconds prior to page generation, Sat Nov 16 19:40:00 2019 (UTC)

BDS Integrity Monitor: Table sorted by SVN
without auto-update (Go to version with 30-sec auto-update)

			Performance metrics				Orbit/Clock error metrics					Link Statistics							
SVN (?)	PRN (?)	Block (?)	URE (plot,?)	FORD (plot,?)	URA (plot,?)	URE/URA (plot,?)	UREE (plot,?)	CLK (plot,?)	RSS (plot,?)	RAC (plot,?)	SIGMA (plot,?)	Total (plot,?)	Good (plot,?)	Bad (plot,?)	Missing (plot,?)	BCE (plot,?)	AOD (plot,?)	Health (plot,?)	SVN (?)
3	1	GEO-2	-	-	-	-	-	-	-	plot	-	19	18	0	1	14	1.0	0	3
5	6	IGSO-2	6.08	2.97	4.00	1.52	1.92	-7.98	2.53	plot	0.00	16	15	0	1	7	3.0	0	5
6	4	GEO-2	1.29	2.77	4.00	0.32	3.81	-4.87	5.96	plot	0.00	18	17	0	1	13	1.0	0	6
7	7	IGSO-2	11.56	7.87	4.00	2.89	2.91	-14.45	3.56	plot	0.00	18	15	0	3	19	1.0	0	7
8	8	IGSO-2	9.11	8.24	4														
9	9	IGSO-2	5.32	4.32	4														
10	10	IGSO-2	5.09	3.98	4														
11	5	GEO-2	3.83	4.93	4														
12	11	MEO-2	2.65	3.28	4														
13	12	MEO-2	2.73	4.86	4														

23 GLO in view (90 sites reporting)

Page generated on Tue Nov 5 12:49:53 2019 (UTC)
Data Epoch: 23 seconds prior to page generation, Tue Nov 5 12:49:30 2019 (UTC)

GLO Integrity Monitor: Table sorted by SVN
without auto-update (Go to version with 30-sec auto-update)

				Performance metrics				Orbit/Clock error metrics					Link Statistics							
SVN (?)	PRN (?)	Orbit (?)	Block (?)	URE (plot,?)	FORD (plot,?)	URA (plot,?)	URE/URA (plot,?)	UREE (plot,?)	CLK (plot,?)	RSS (plot,?)	RAC (plot,?)	SIGMA (plot,?)	Total (plot,?)	Good (plot,?)	Bad (plot,?)	Missing (plot,?)	BCE (plot,?)	AOD (plot,?)	Health (plot,?)	SVN (?)
719	20		M	0.45	0.59	99.00	0.00	0.22	0.25	0.75	plot	0.00	20	16	2	2	0	0.0	0	719
720	19		M	1.55	0.41	99.00	0.02	0.86	0.72	2.26	plot	0.00	21	16	1	4	0	0.0	0	720
721	13		M	0.72	0.77	99.00	0.01	0.52	-0.75	3.41	plot	0.00	19	18	0	1	0	0.0	0	721
723	10		M	-	-	-	-	-	-	-	plot	-	13	0	0	13	0	0.0	0	723
730	1		M	2.86	0.71	99.00	0.03	0.18	2.77	1.15	plot	0.00	20	17	0	3	0	0.0	0	730
731	22		M	0.54	0.46	99.00	0.01	0.34	0.24	1.70	plot	0.00	42	39	2	1	0	0.0	0	731
732	23		M	1.88	0.64	99.00	0.02	0.67	-1.61	4.72	plot	0.00	38	37	0	1	0	0.0	0	732

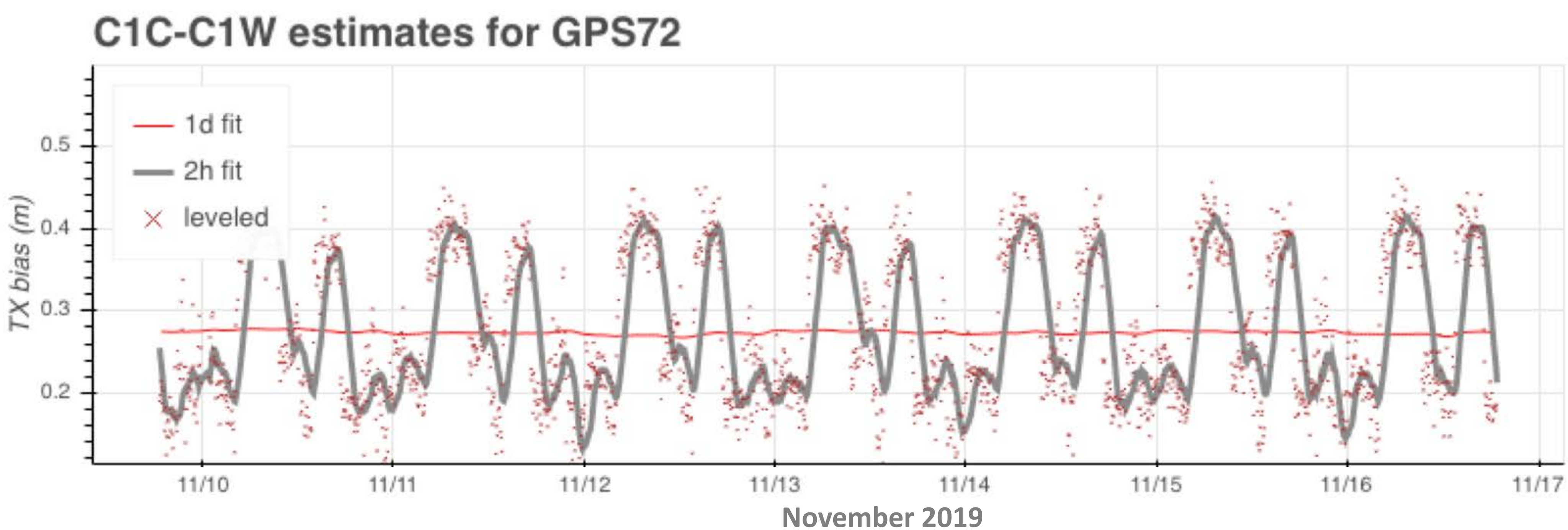
Inter-Signal Bias Monitoring

GDGPS monitors inter-signal biases (aka differential code biases) for GPS, BeiDou, and Galileo

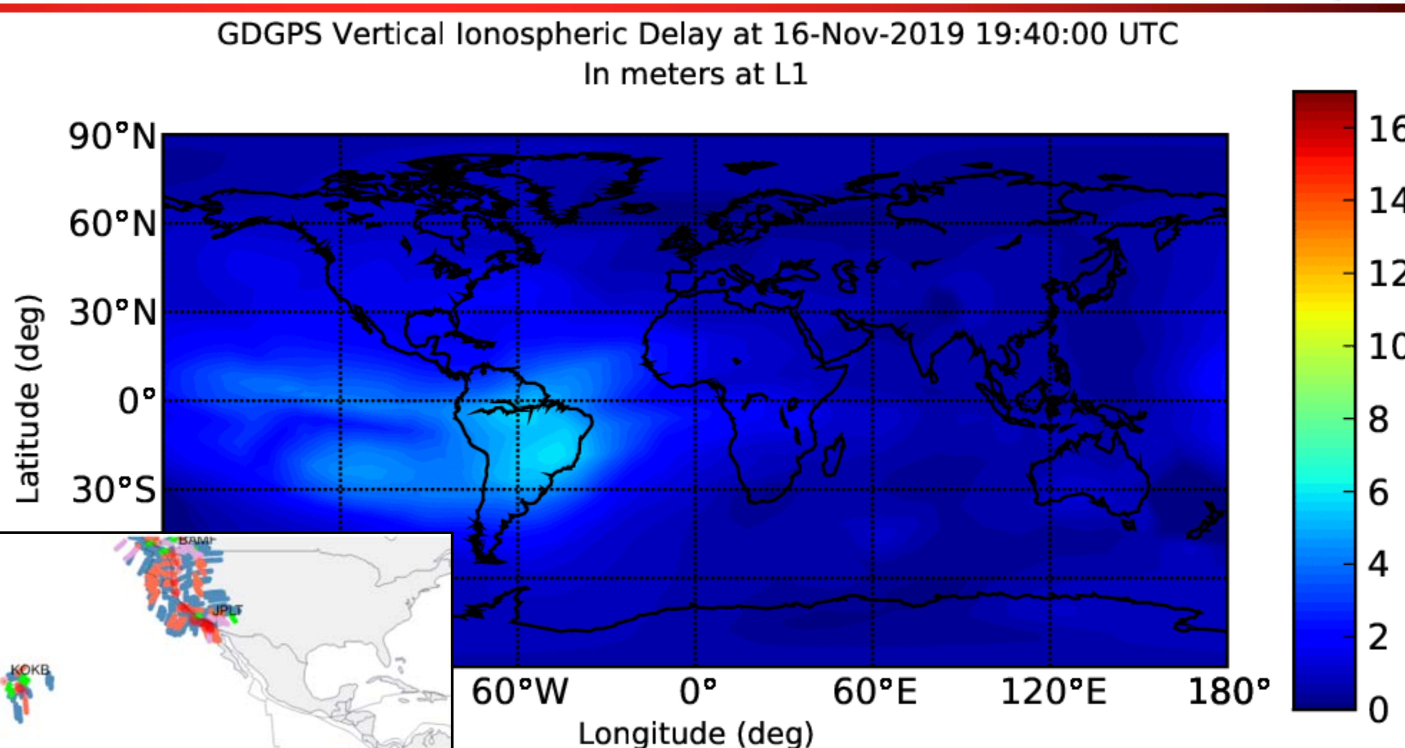
JPL's *Tgd* inter-signal bias estimates have been broadcasted by GPS for two decades

Special high rate tracking required for monitoring GPS flex power impact on signal biases

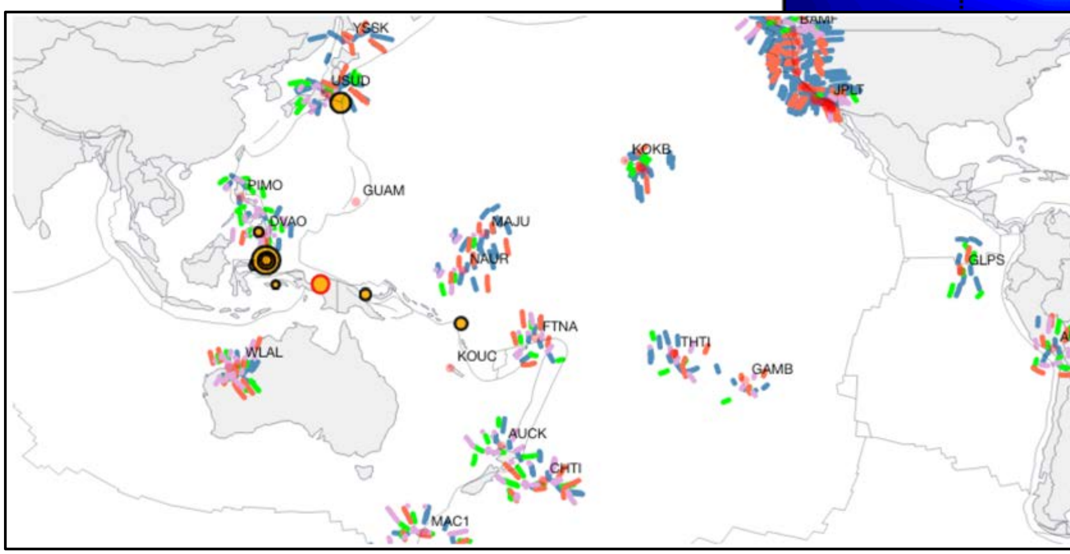
- Onset of regular Flex Power regime in January 2017
- Occasional other Flex Power regimes
- Induced signal biases adversely impact precision orbit determination and positioning applications



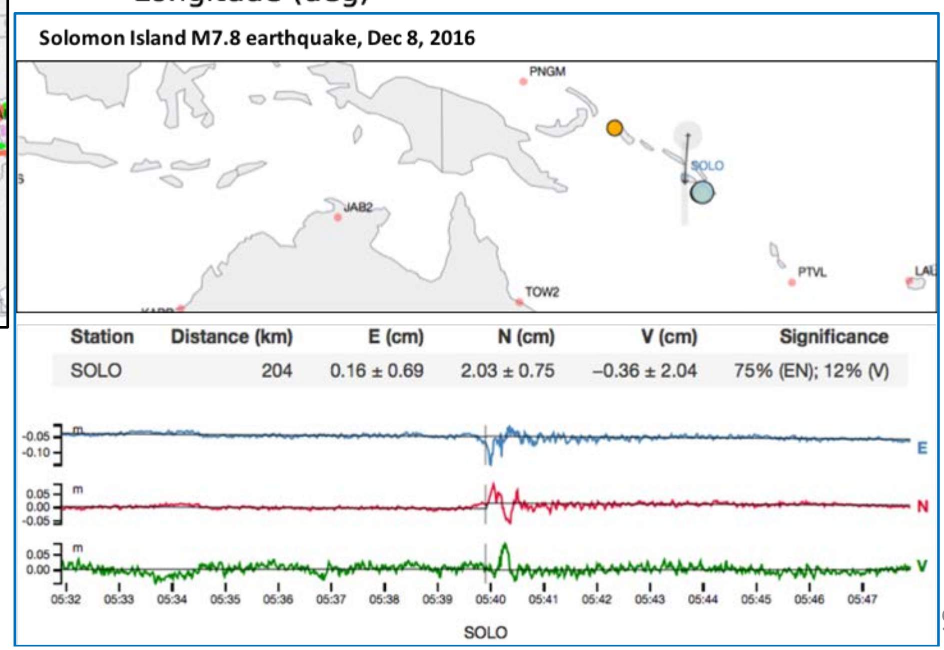
GDGPS Environmental and Natural Hazard Monitoring



Tsunami monitoring in the Pacific through ionospheric sensing



Global Earthquake monitoring



Situational Assessment and Mitigation of Threats to GPS Applications with the GDGPS System

Threats include:

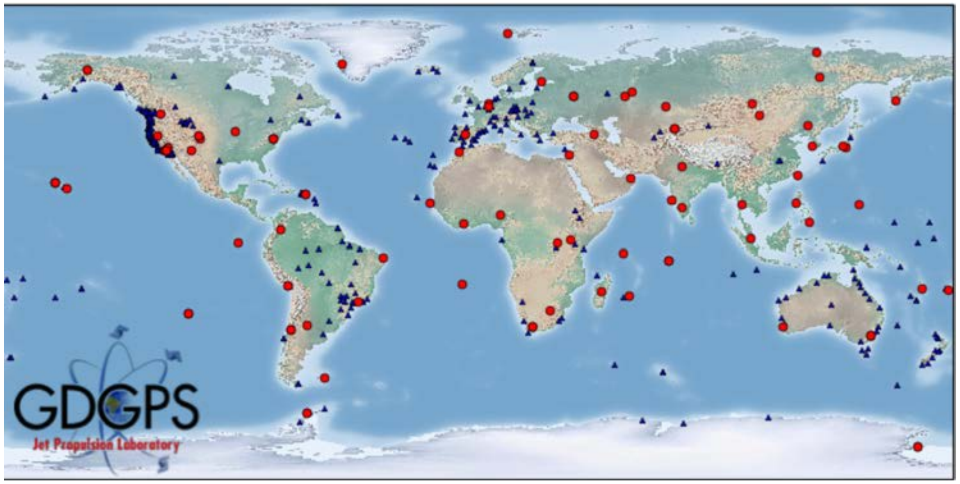
- Integrity failures
- Jamming
- spoofing (of ranging signals and broadcast message)

Approach:

- Use global and regional real-time monitoring networks; exploit the inherent resiliency of globally-tracked GPS
- Authenticate GPS signals based on unspoofable, unjammable GDGPS System
- Apply classical monitoring and big data mining techniques

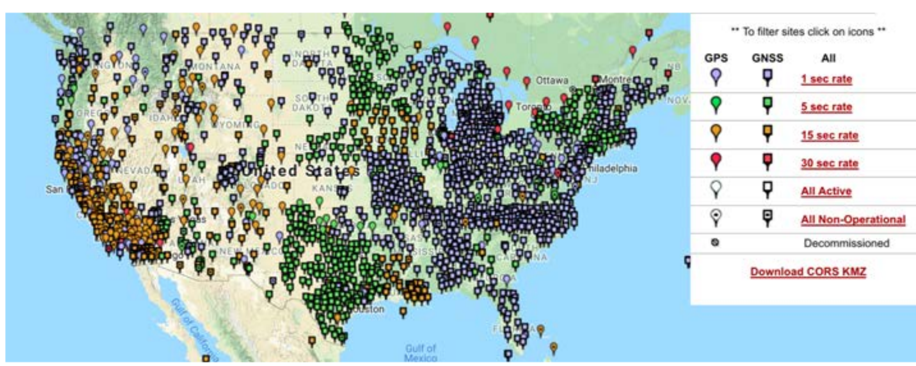
Beneficiaries:

- Responsible agencies (for example, DHS, DOT)
- Connected users (for example, power grids, communications grids)



Threat Analysis and Potential Mitigation by GDGPS

Threats	Mitigation Leveraging GDGPS
Global	
Taking over a GPS satellite	***Global integrity monitoring***
Regional (~500 km)	
Spoofing, jamming	***Centralized situational assessment*** using existing GDGPS tracking sites; incorporate hundreds of existing U.S. tracking sites ***Monitor:*** SNR, range measurements against established models, patterns (multipath, residuals,…), clock jumps, regional comparisons ***Big data, crowd-sourcing situational assessment***
Point	
Spoofing, jamming	***Connected sites get information, validation from a trusted source***: Nav messages, ephemeris predictions (already used by millions of cell phone users) ***Smarter receivers:*** RAIM, signal analysis,…



NGS CORS Network

Galileo Overtakes GPS in Support of Civilian Applications

Civilian applications appear as low priority for GPS; Galileo steps up to the challenge

Capability Promoting Precision Civilian Applications	GPS	Galileo
Laser retro reflectors	No (to be reintroduced with SV11)	Yes
Antenna phase calibrations (Earth coverage)	Not for GPS III Some for Block IIR (courtesy LM; inconsistent with science community calibrations) None for Block IIF	Yes (Consistent with science community calibrations – about to be adopted as standard for terrestrial reference frame)
Attitude model	No	Yes
Radiation pressure properties	No	Yes
Signal in space accuracy (URE)	~0.5 m RMS ~0.4 m Median	~0.4 m RMS 0.2 m Median
Mean Age of Data (AOD)	~12 hours	Less than 1 hour
Stable transmit power; stable inter-signal biases	No (Flex Power)	Yes

Going forward, GPS IIIF is considering designs that may further degrade science applications

Why Wait?

Existing global and regional GPS tracking networks, technologies, and operational capabilities enable effective mitigation to some threats to sensitive GPS infrastructure at the U.S. and beyond

- Centralized situational assessment of RFI attacks
- Trusted data services to monitor/replace the broadcast ephemeris
- ‘Smarts’ can be implemented outside the receiver, and be both distributed and centralized

GDGPS real-time augmentation and situational assessment capabilities extend to all GNSS

Why wait for a more perfect system to enhance infrastructure resiliency?

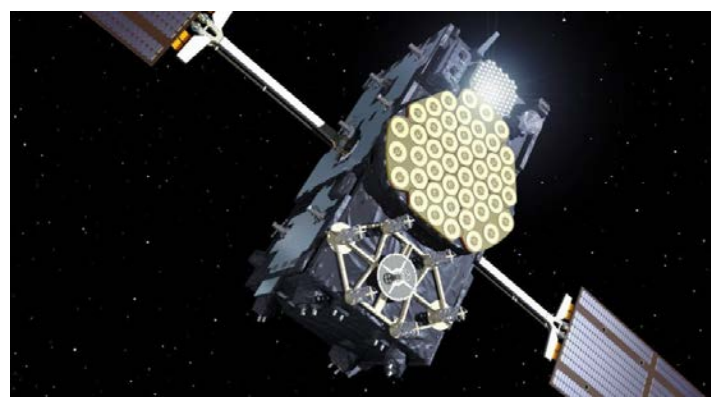
- Learn from the DoT interminable quest for a perfect civil signal monitoring service

Will GPS become a backup system to Galileo in civilian application?

- Has GPS given up on maintaining leadership in civilian and science applications?
- Will geodetic standards, used operationally by GPS (e.g., ITRF) be referenced to Galileo?

GPS IIIF

GPS III



Galileo