Update on GNSS Performance Monitoring

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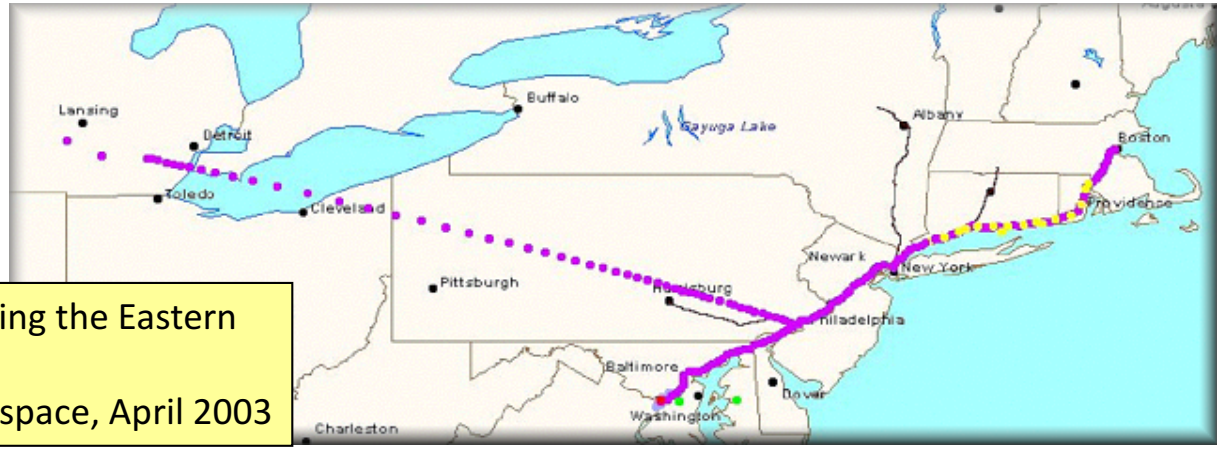
15 Years of JPL GPS Performance Monitoring for the Air Force

Initiated by Aerospace Corporation following the SVN 22 event of November 5, 2002

The active Rubidium clock on the Block IIA spacecraft experienced a frequency jump while the satellite was not monitored by the OCS for nearly 2 hours



GPS-based arrival-time system on a train traversing the Eastern seaboard saw extraordinary position errors.
Source: J. Langer, Aerospace, April 2003

The JPL GPS performance monitoring service was jointly developed by JPL and Aerospace, with input from the 2SOPS operators

- Funded in recent years by 2SOPS operational budget
- Continuously refined and augmented with additional capabilities
- Use tracking data from 80+ sites in the Global Differential GPS (GDGPS) network
- GDGPS real-time orbit and clock solutions are used as *Truth*

Monitor key performance metrics of the broadcast ephemeris and the navigation signals

- User range accuracy, due to broadcast or ranging signal
- Correctness of key broadcast parameters
- Satellite observability assessment
- 30 second latency

Snapshot of the GDGPS CNAV Monitoring Web Page

JPL's Performance Monitor of the GPS Broadcast Navigation Message:

CNAV-L2

Go To: LNAV

19 GPS in view (71 sites reporting)

Page generated on Fri Jun 23 23:50:22 2017 (UTC)
Data Epoch: 22 seconds prior to page generation, Fri Jun 23 23:50:00 2017 (UTC)

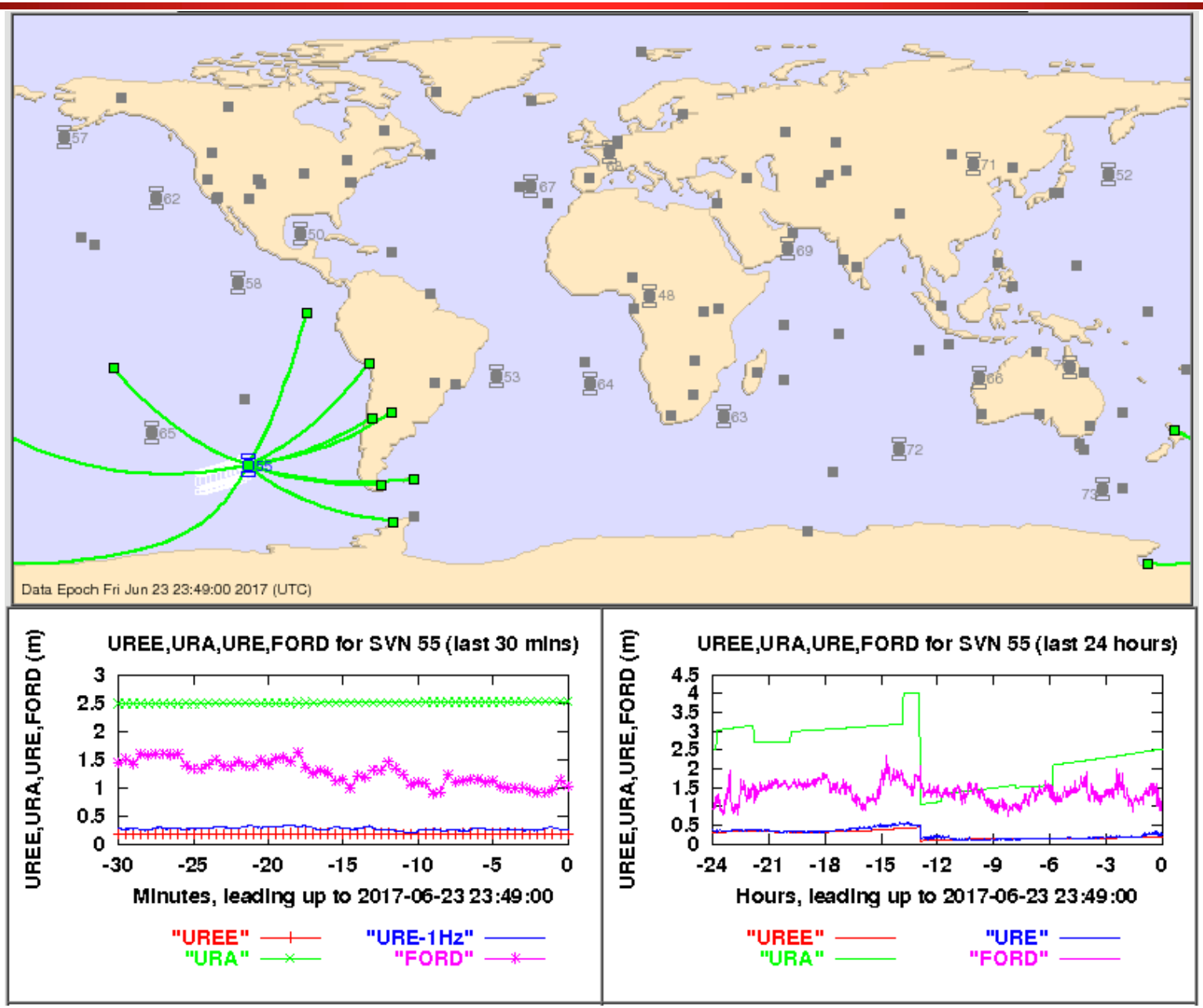
GPS Integrity Monitor: Table sorted by SVN
without auto-update *(Go to version with 30-sec auto-update)*

				Performance metrics				Orbit/Clock error metrics					UTC Model		Link Statistics						Health			
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,?)	L1 (plot,?)	L2 (plot,?)	L5 (plot,?)	SVN (?)
48	7	A-4	IIR-M	0.21	1.41	3.44	0.06	0.23	-0.02	0.42	plot	0.03	0.872	17.0	41	12	29	0	13	17.0	0	0	1	48
50	5	E-3	IIR-M	0.47	1.15	2.48	0.19	0.28	-0.25	1.64	plot	0.03	0.916	12.5	26	24	0	2	14	12.5	0	0	1	50
52	31	A-2	IIR-M	0.52	3.18	2.75	0.19	0.17	-0.67	0.57	plot	0.03	0.905	14.2	56	27	29	0	19	14.2	0	0	1	52
53	17	C-4	IIR-M	1.20	1.93	2.27	0.53	0.41	-1.47	2.02	plot	0.03	0.912	11.2	22	21	0	1	17	11.2	0	0	1	53
55	15	F-2	IIR-M	0.39	0.95	2.38	0.16	0.17	-0.25	0.97	plot	0.04	0.912	11.2	41	12	29	0	8	11.2	0	0	1	55
57	29	C-1	IIR-M	0.78	1.96	2.48	0.31	0.21	-0.68	1.38	plot	0.03	0.916	12.5	20	20	0	0	16	12.5	0	0	1	57
58	12	B-4	IIR-M	0.21	0.97	2.71	0.08	0.15	0.36	0.26	plot	0.03	0.872	17.0	25	25	0	0	14	17.0	0	0	1	58
62	25	B-2	IIF	0.12	1.39	2.20	0.06	0.28	0.36	0.64	plot	0.03	0.962	7.2	28	28	0	0	20	7.2	0	0	1	62
63	1	D-2	IIF	0.20	1.30	1.62	0.12	0.15	0.05	0.67	plot	0.03	0.803	4.5	79	21	58	0	14	4.5	0	0	1	63
64	30	A-3	IIF	0.21	0.81	2.29	0.09	0.25	-0.33	1.11	plot	0.03	0.928	8.5	47	17	29	1	10	8.5	0	0	1	64
65	24	A-1	IIF	0.34	1.50	2.31	0.15	0.45	0.11	0.68	plot	0.03	0.826	3.2	13	12	0	1	7	3.2	0	0	1	65
66	27	C-2	IIF	0.30	3.04	1.64	0.18	0.06	0.26	0.38	plot	0.03	0.822	4.7	73	14	58	1	10	4.7	0	0	1	66
67	6	D-4	IIF	0.42	0.71	2.20	0.19	0.19	-0.29	1.19	plot	0.03	0.962	7.2	31	31	0	0	18	7.2	0	0	1	67
68	9	F-3	IIF	0.14	1.03	2.20	0.06	0.13	0.00	0.64	plot	0.03	0.962	7.2	47	17	27	3	17	7.2	0	0	1	68
69	3	E-1	IIF	0.28	1.65	1.57	0.18	0.12	0.18	0.61	plot	0.03	0.805	3.7	53	24	29	0	17	3.7	0	0	1	69
70	32	F-1	IIF	0.26	3.58	4.23	0.06	0.20	-0.09	1.26	plot	0.03	0.944	24.0	46	17	29	0	16	24.0	0	0	1	70
71	26	B-1	IIF	0.36	3.67	2.40	0.15	0.16	0.20	0.31	plot	0.04	0.953	10.0	49	20	29	0	18	10.0	0	0	1	71
72	8	C-3	IIF	0.71	2.18	2.46	0.29	0.12	0.60	0.39	plot	0.03	0.928	8.5	44	15	29	0	10	8.5	0	0	1	72
73	10	E-2	IIF	0.18	2.71	4.23	0.04	0.13	-0.07	0.84	plot	0.03	0.944	24.0	42	13	29	0	10	24.0	0	0	1	73
SVN	PRN	Orbit	Block	URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	dUTC	dtRef	Total	Good	Bad	Missing	BCE	AOD	L1	L2	L5	SVN

Recently-added capabilities:

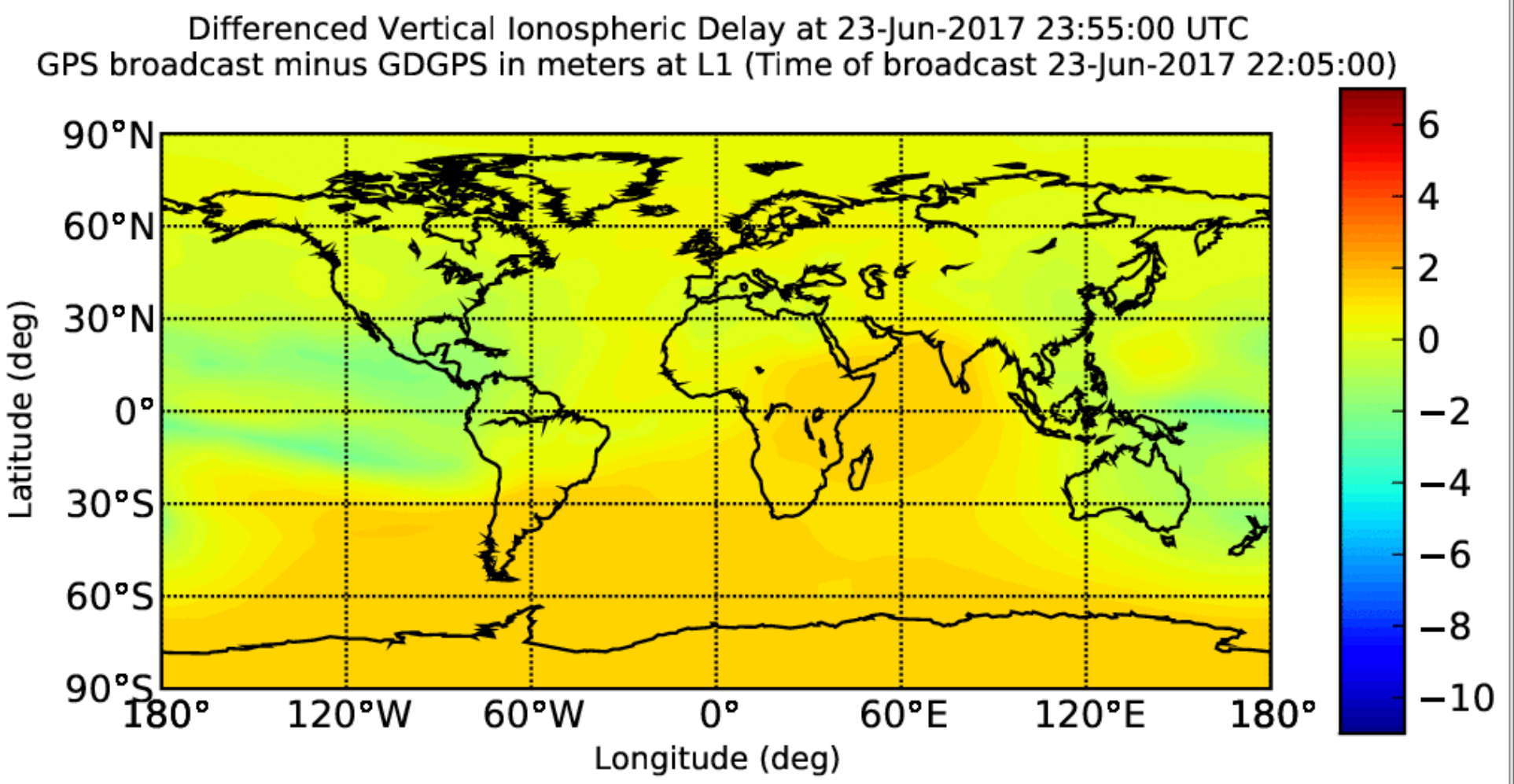
- CNAV monitoring on L2 and L5
- UTC model (after the Jan 2016 event)
- Differential Code Biases monitoring
- GNSS time transfer parameters (in 2018)

Snapshot of the GDGPS CNAV Monitoring Web Page (contd.)



Monitoring in Support of Single-Frequency Users

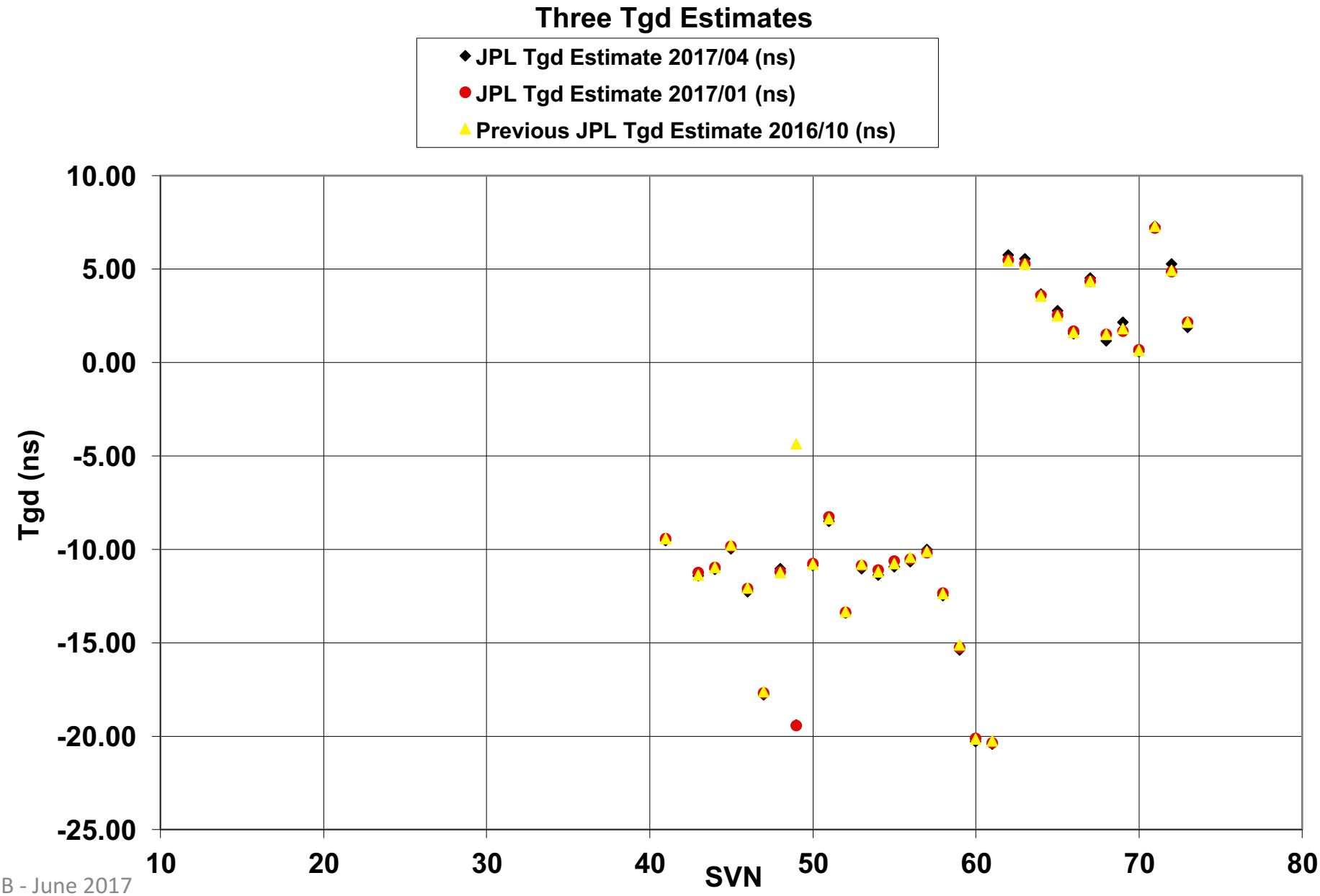
Broadcast (Klobuchar) Ionosphere Monitor
Updated every 5 minutes



Leveraging JPL's ionospheric expertise and dense global network

Monitoring *and Upload* of Inter-Frequency Biases

JPL's *Tgd* estimates are being broadcast by GPS; Updated quarterly and on change

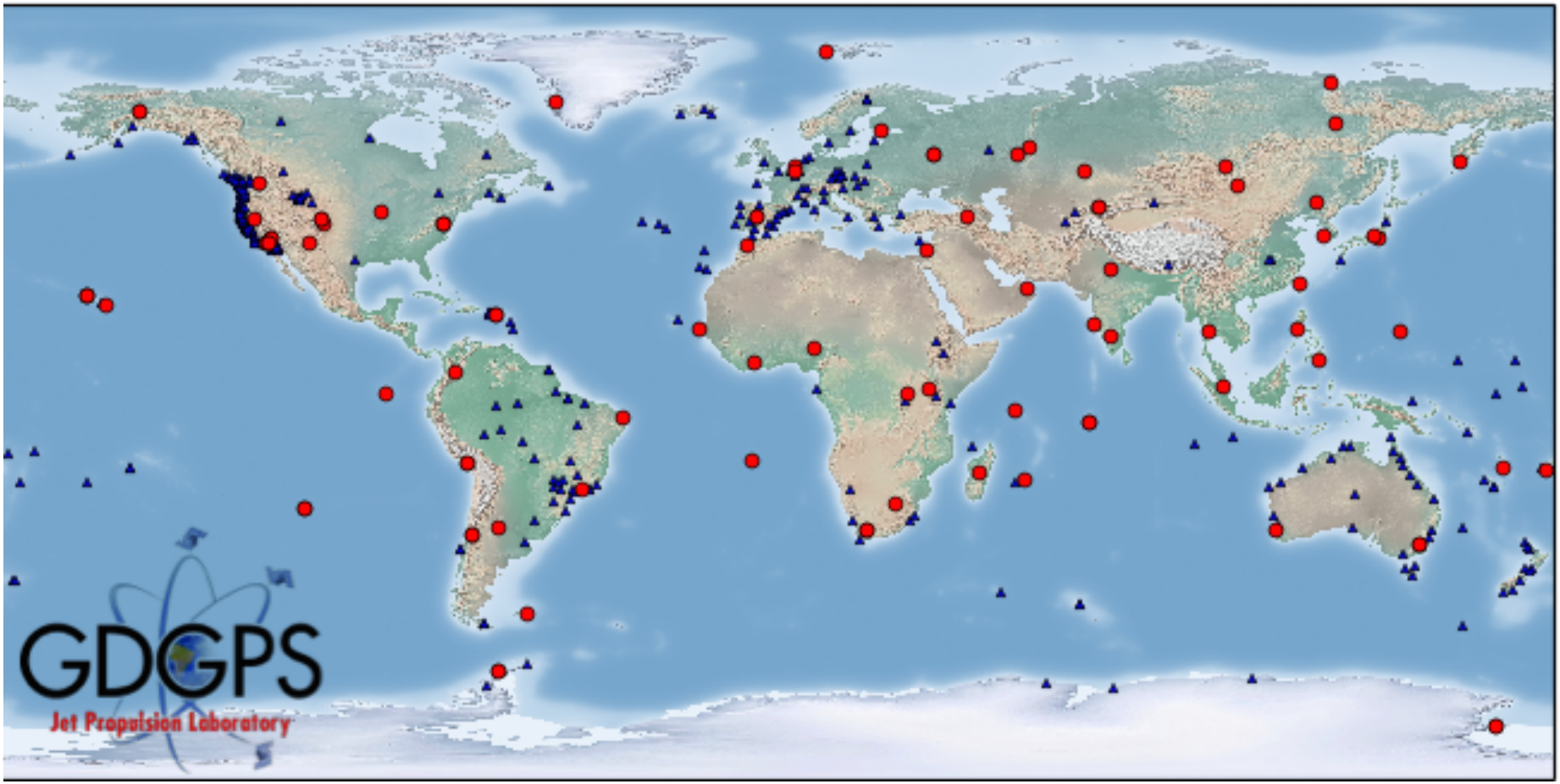


The Foundation: Extremely Redundant Global Real-Time Tracking Network

80+ global tracking sites deployed, controlled, operated, and maintained by JPL's GDGPS System

- Hardware and software fully owned and controlled by JPL
- Decades of site stability, quality, and continuity
- **25-fold** observation redundancy, on average, enable strong majority voting schemes

Hundreds of contributed sites operated by a variety of partners, U.S. and foreign agencies (e.g., NSF, BKG, GA) provide additional level of redundancy and density of coverage



CSM, Once Again

JPL already monitors and reports all the key navigation metrics of the GPS civil signals

JPL already possesses all the data needed to verify 90% of the Civil Monitoring Performance Specifications (CMPS)

JPL proposed to monitor 98% of the CMPS within a year

- Leveraging the significant NASA and USAF investment in the GDGPS System
- PNT AB recommended using the cost-effective GDGPS system for CSM (Parkinson, 2013)
- The proposal was analyzed by the FAA 2014 CSM Trade Study Team and found attractive

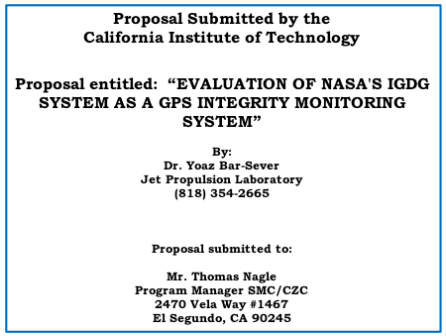
recommendations are:

1. Submit a request for proposal to Raytheon for buying P1-P2 with an option for P3 requirements
2. Submit a request for proposal to NASA JPL for buying and maintaining the Non-OCX element with SQM monitoring
3. The civil community should engage with Air Force Space Command to establish operational procedures for GPS control of signals used by the civil community that utilize increasing amounts of Non-OCX monitoring information over time.

GPS Civil Signal Monitoring Trade Study Report
DOT-VNTSC-FAA-14-06
March 7, 2014

Refined proposal (worked with FAA) submitted to FAA in October 2015. Then silence.

We could have had CSM 15 years ago!



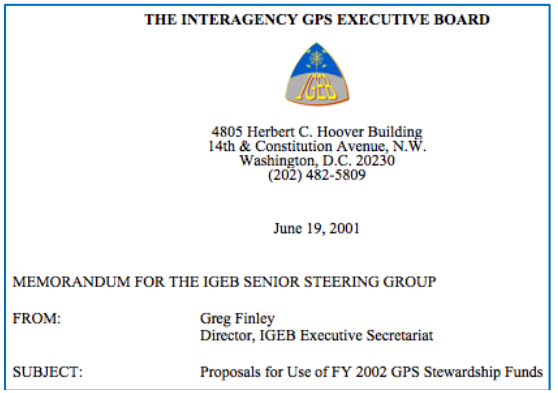
Proposal Submitted by the
California Institute of Technology

Proposal entitled: "EVALUATION OF NASA'S IGDG SYSTEM AS A GPS INTEGRITY MONITORING SYSTEM"

By:
Dr. Yoaz Bar-Sever
Jet Propulsion Laboratory
(818) 354-2665

Proposal submitted to:

Mr. Thomas Nagle
Program Manager SMC/CZC
2470 Vela Way #1467
El Segundo, CA 90245



THE INTERAGENCY GPS EXECUTIVE BOARD

4805 Herbert C. Hoover Building
14th & Constitution Avenue, N.W.
Washington, D.C. 20230
(202) 482-5809

June 19, 2001

MEMORANDUM FOR THE IGEB SENIOR STEERING GROUP

FROM: Greg Finley
Director, IGEB Executive Secretariat

SUBJECT: Proposals for Use of FY 2002 GPS Stewardship Funds

Real-Time GNSS Performance Monitoring Available now

GDGPS is monitoring the civil signals from GLONASS, BeiDou, and Galileo. Soon, QZSS

- IRNSS monitoring is being assessed
- 100% redundant global coverage

Full RTGX-based development server processing BDS broadcast

14 BDS in view (42 sites reporting)

Page generated on Fri Jun 23 20:08:18 2017 (UTC)
Data Epoch: 18 seconds prior to page generation, Fri Jun 23 20:08:00 2017 (U

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

SVN	PRN	Orbit	Block	Performance metrics				Orbit/Clock error metrics					Link Statist			
				URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	Total	Good	Bad	M
101	1	GEO-1		-	-	-	-	-	-	-	plot	-	29	21	3	
103	3	GEO-1		1.77	3.84	4.00	0.44	1.07	-0.71	2.27	plot	0.03	29	22	3	
104	4	GEO-1		2.69	2.87	4.00	0.67	0.82	-2.41	5.79	plot	0.03	29	20	3	
105	5	GEO-1		1.41	2.42	4.00	0.35	0.78	1.75	4.45	plot	0.03	19	13	2	
106	2	GEO-1		0.39	2.01	4.00	0.10	0.39	-0.30	2.60	plot	0.03	26	15	3	
201	6	IGSO-1		2.00	3.09	4.00	0.50	0.17	-1.95	1.18	plot	0.03	25	17	1	
202	7	IGSO-1		4.16	5.98	4.00	1.04	2.52	-6.68	2.64	plot	0.03	26	19	2	
203	8	IGSO-1		2.20	3.98	4.00	0.55	3.45	-5.63	3.75	plot	0.04	23	15	3	
204	9	IGSO-1		2.04	1.81	4.00	0.51	0.86	1.19	1.54	plot	0.03	22	18	1	
205	10	IGSO-1		3.53	3.83	4.00	0.88	3.46	0.08	3.49	plot	0.03	26	21	3	
208	13	IGSO-1		14.28	12.91	4.00	3.57	3.68	10.60	3.76	plot	0.04	24	17	3	
303	11	MEO-1		3.45	2.57	4.00	0.86	1.36	2.12	2.58	plot	0.04	20	12	2	
304	12	MEO-1		3.49	3.08	4.00	0.87	0.99	2.60	3.71	plot	0.04	14	11	2	
306	14	MEO-1		1.85	1.84	4.00	0.46	1.53	0.32	1.57	plot	0.03	28	21	3	
SVN	PRN	Orbit	Block	URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	Total	Good	Bad	M

Full RTGX-based development server processing GLO broadcast

24 GLO in view (59 sites reporting)

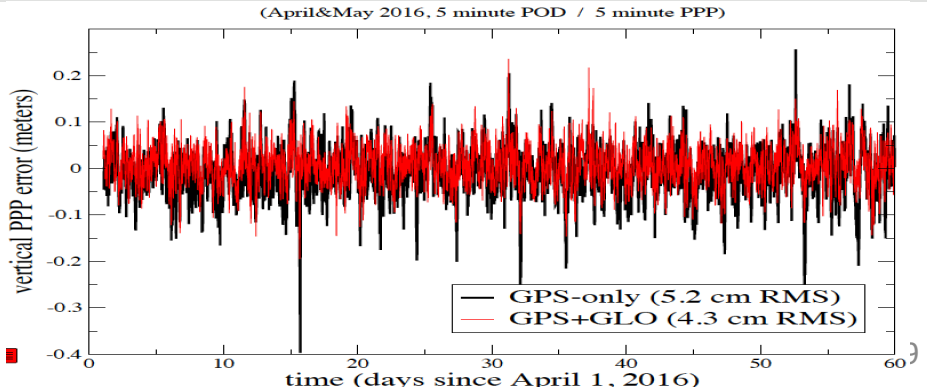
Page generated on Fri Jun 23 19:51:48 2017 (UTC)
Data Epoch: 18 seconds prior to page generation, Fri Jun 23 19:51:30 2017 (UTC)

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

SVN	PRN	Orbit	Block	Performance metrics				Orbit/Clock error metrics					Link Statistics					AOD	Health	SVN
				URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	Total	Good	Bad	Missing	BCE			
715	14	M		4.21	3.47	99.00	0.04	0.58	4.72	1.96	plot	0.03	10	9	1	0	9	0.0	0	715
716	15	M		1.41	2.30	99.00	0.01	0.62	1.29	4.44	plot	0.03	15	13	2	0	18	0.0	0	716
717	10	M		-	-	-	-	-	-	-	plot	-	17	15	2	0	25	0.0	0	717
719	20	M		1.46	1.65	99.00	0.01	0.86	0.67	3.89	plot	0.03	10	8	2	0	10	0.0	0	719
720	19	M		1.32	1.57	99.00	0.01	1.36	-0.10	7.86	plot	0.03	16	12	4	0	21	0.0	0	720
721	13	M		0.41	3.35	99.00	0.00	0.78	-0.41	1.74	plot	0.03	12	11	0	1	11	0.0	0	721
723	12	M		-	-	-	-	-	-	-	plot	-	15	1	0	14	13	0.0	0	723
730	1	M		2.45	2.64	99.00	0.02	0.11	2.36	0.51	plot	0.02	23	20	3	0	22	0.0	0	730
731	22	M		-	-	-	-	-	-	-	plot	-	17	15	1	1	13	0.0	0	731
732	23	M		1.34	3.71	99.00	0.01	0.34	1.13	2.06	plot	0.03	13	10	1	2	16	0.0	0	732
733	6	M		1.21	3.01	99.00	0.01	0.75	0.47	1.69	plot	0.03	14	10	1	3	15	0.0	0	733
734	5	M		3.33	2.64	99.00	0.03	0.60	2.83	2.65	plot	0.03	11	9	1	1	8	0.0	0	734
735	24	M		0.11	1.78	99.00	0.00	0.54	-0.45	0.70	plot	0.02	23	19	1	3	15	0.0	0	735
736	16	M		0.41	3.37	99.00	0.00	0.46	-0.78	1.45	plot	0.03	17	14	2	1	24	0.0	0	736
742	4	M		-	-	-	-	-	-	-	plot	-	9	8	0	1	8	0.0	0	742
743	8	M		5.01	1.97	99.00	0.05	0.25	-5.20	1.16	plot	0.02	18	15	2	1	24	0.0	0	743
744	3	M		4.83	3.95	99.00	0.05	0.84	-5.33	4.63	plot	0.03	16	13	2	1	16	0.0	0	744
745	7	M		1.38	2.26	99.00	0.01	0.33	-1.70	0.56	plot	0.03	18	15	3	0	18	0.0	0	745
747	2	M		4.31	1.85	99.00	0.04	0.80	3.52	1.44	plot	0.02	22	13	1	8	19	0.0	0	747
802	9	K1		2.48	3.65	99.00	0.03	0.76	-3.04	3.42	plot	0.03	23	19	4	0	29	0.0	0	802
851	17	M		2.49	2.45	99.00	0.03	0.76	-3.08	3.11	plot	0.02	24	22	2	0	21	0.0	0	851
853	11	M		0.51	2.32	99.00	0.01	0.56	-0.05	0.96	plot	0.03	15	14	1	0	18	0.0	0	853
854	18	M		2.90	2.88	99.00	0.03	0.52	2.38	0.72	plot	0.02	26	22	4	0	26	0.0	0	854
855	21	M		3.12	2.02	99.00	0.03	0.40	-3.46	1.49	plot	0.03	14	13	1	0	5	0.0	0	855
SVN	PRN	Orbit	Block	URE	FORD	URA	URE/URA	UREE	CLK	RSS	RAC	SIGMA	Total	Good	Bad	Missing	BCE	AOD	Health	SVN

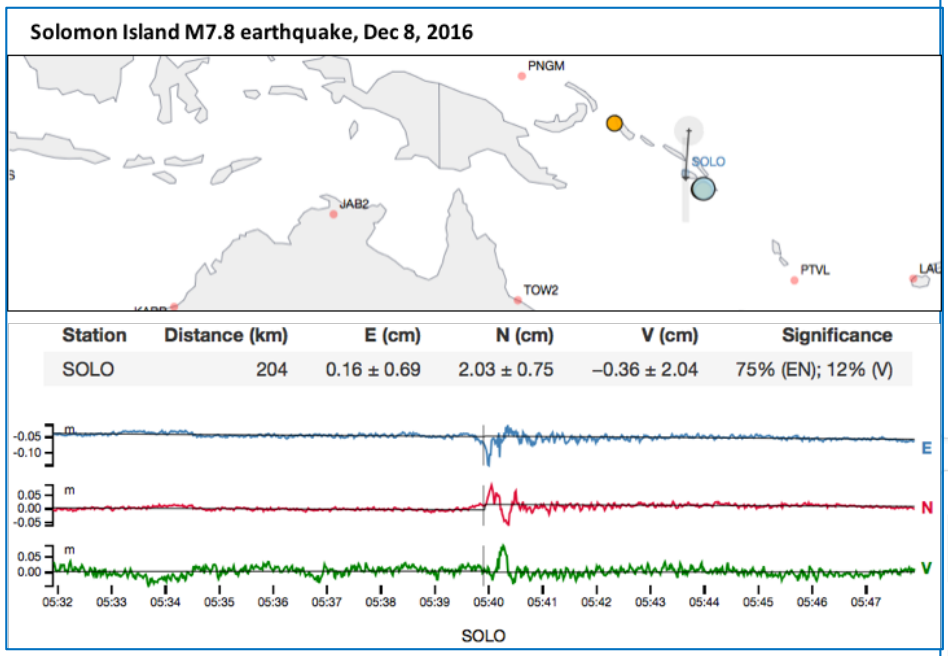
High accuracy real time orbit and clock solutions provide some benefits relative to GPS-only in certain applications

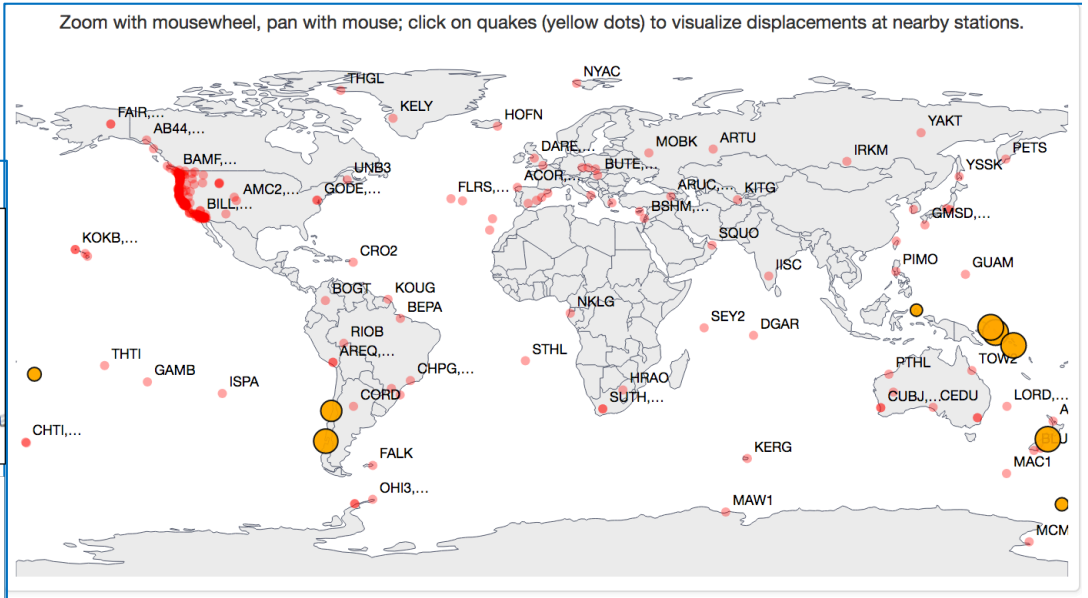
- e.g. Earthquake monitoring:



GDGPS Real-Time Natural Hazard Monitoring

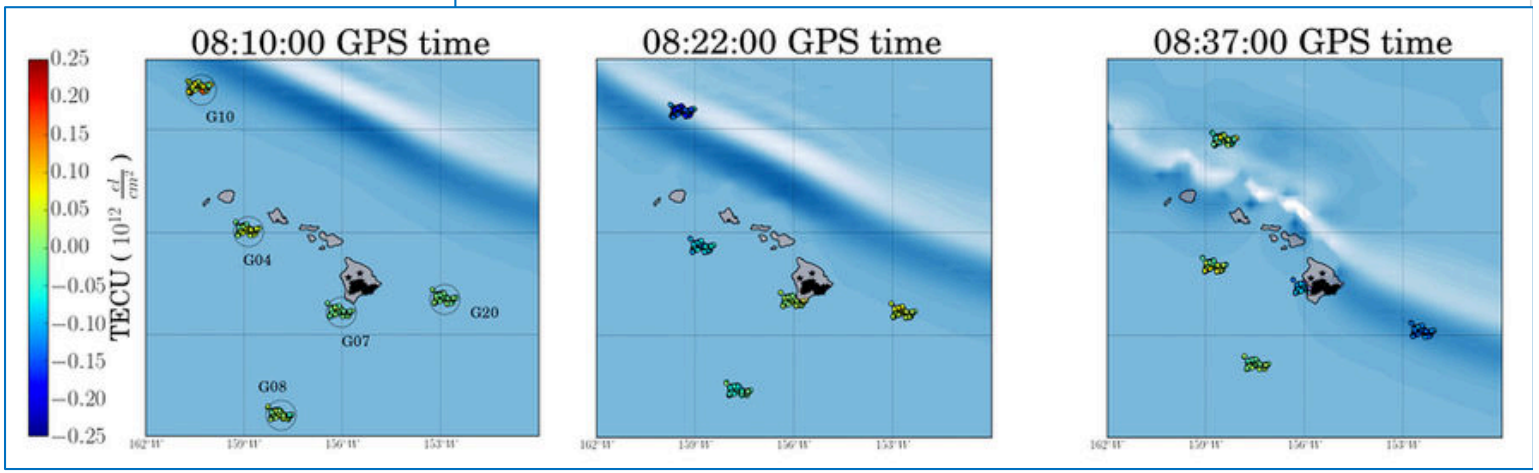
Displacement monitoring for 200+ sites at https://ga.gdgps.net





Magnitude	Place	Time	ID
5	39km SSE of Tobelo, Indonesia	Wed, 26 Apr 2017 04:52:02 GMT	us10008kxh
5.2	282km NNW of Scott Island Bank, Antarctica	Tue, 25 Apr 2017 21:20:27 GMT	us10008kv0
5.3	112km SE of Pangai, Tonga	Tue, 25 Apr 2017 14:35:14 GMT	us10008kp9

Real-Time detection of tsunami ionospheric disturbances with GNSS ground tracking
(Savastano et al., Nature, 2017)



Conclusions

Existing and proven GDGPS tracking networks, technologies, and operational capabilities can provide effective and low cost GPS civil signal monitoring

JPL's GDGPS System already tracks and monitors GLONASS, BeiDou, and Galileo on a global scale

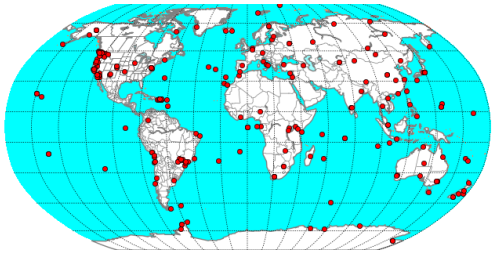
- Can be used to alleviate concerns in the U.S. about incorporating GNSS signals into certain regulated services, such as E-911 geolocation
- The system is already being used commercially to provide Assisted GNSS services to millions of mobile users

The Global Differential GPS (*GDGPS*) System

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

Full GNSS capabilities: GPS, GLONASS, BeiDou, Galileo

Real-Time Tracking Network (200+ sites)

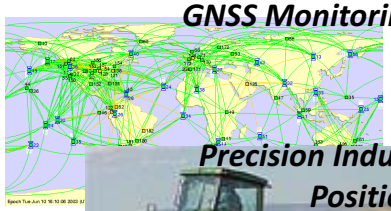


Measurements

Triple Hot Redundant Operation Centers

Products, Services

GNSS Monitoring



Precision Industrial Positioning

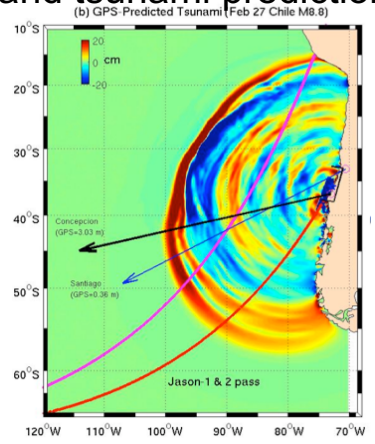
Personal Geolocation

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

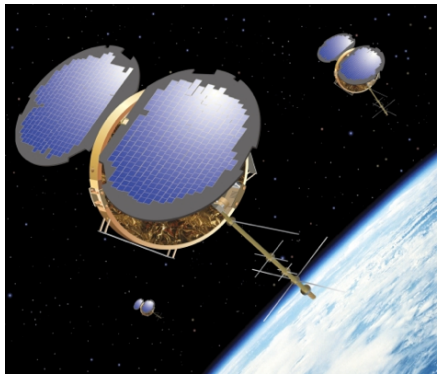
Time-critical environmental monitoring services

Repeat path interferometry with UAV-SAR

Earthquake monitoring and tsunami prediction



GNSS navigation data for Radio Occultations



Space weather monitoring