HOW GLONASS FAILED FOR 11 HOURS
AND MULTI-GNSS SURVIVED

Frank van Diggelen,
Stanford PNT
29 Oct 2014
v1.4

but first ...
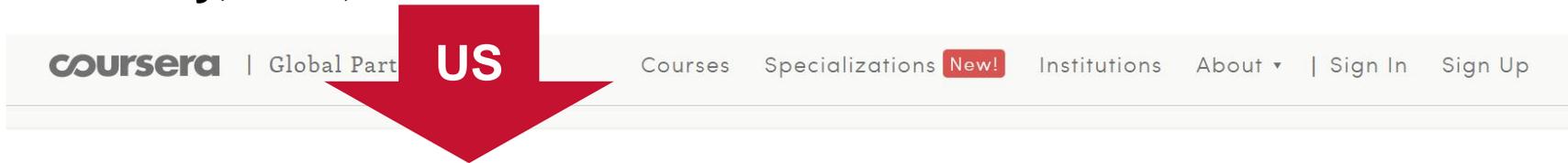
THE FIRST GPS MOOC

(5 minutes, followed by advertised talk)

Frank van Diggelen, Per Enge
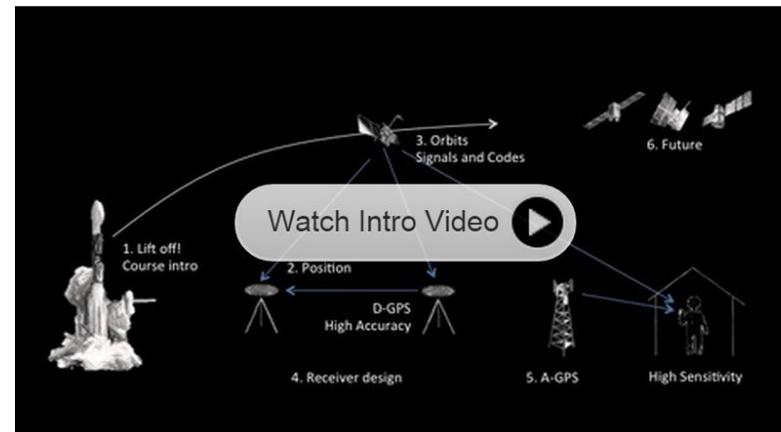
WHAT'S A MOOC? "MASSIVE OPEN ONLINE COURSE" *BROADCOM*

- **Free online course**

- **Video-lectures, interactive quizzes**

- **Pioneered at Stanford (Sebastian Thrun)**

- **Udacity, EdX, Coursera**

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GPS: An Introduction to Satellite Navigation, with an interactive Worldwide Laboratory using Smartphones

Explore the fundamentals of the Global Positioning System (GPS) and how it works by conducting "backyard" laboratory experiments on your own mobile device. Learn the basics of satellite navigation and witness the power of a network with planet-wide coverage. Gain a deeper understanding of GPS and its role in our lives, while interacting with a worldwide community of learners and backyard scientists.
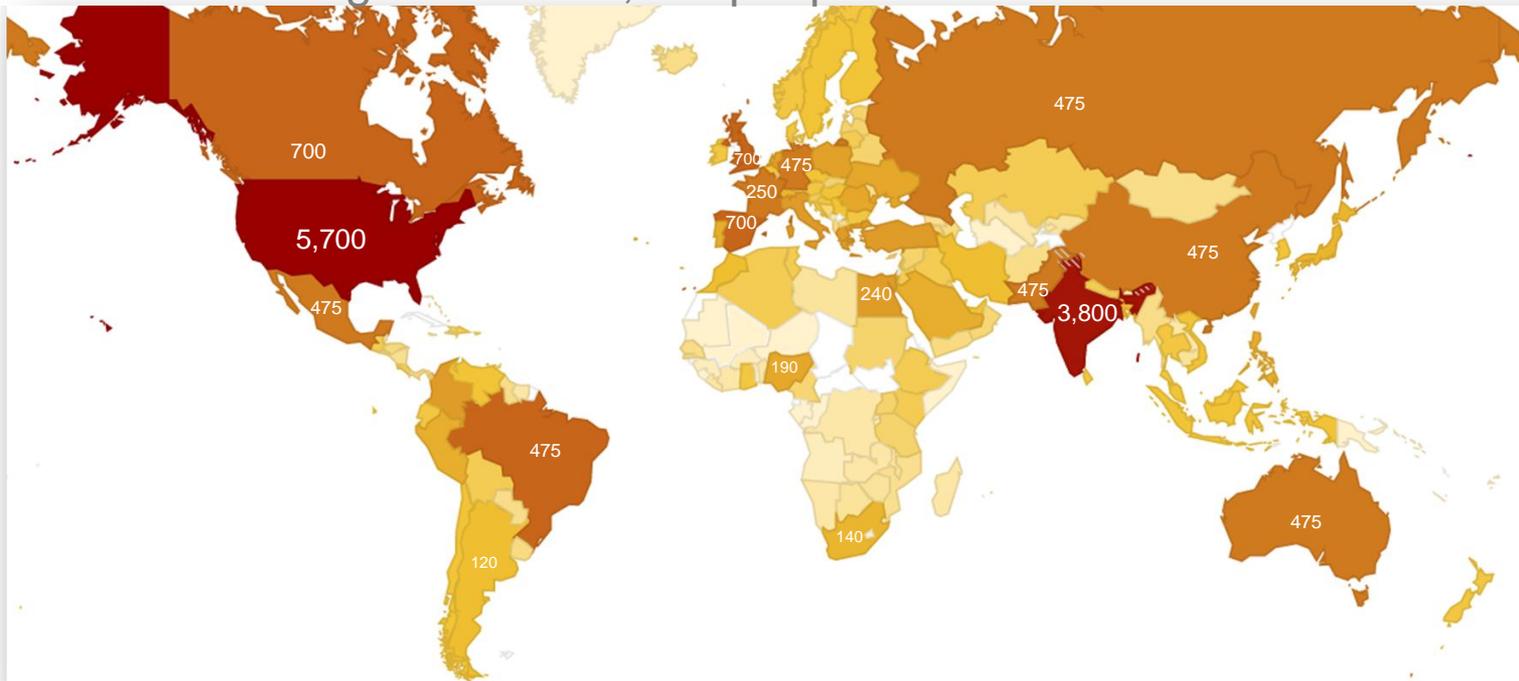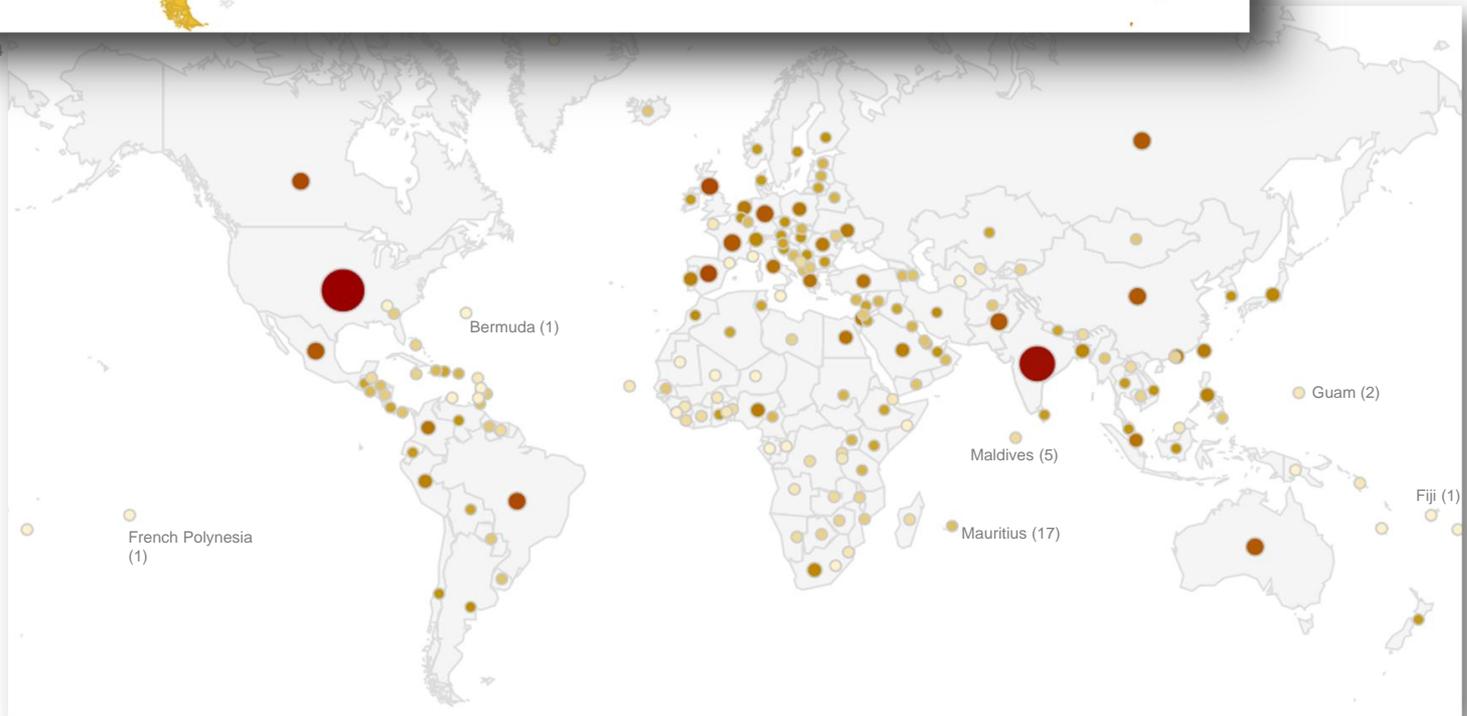
Watch Intro Video ▶

1. Lift off! Course intro
2. Position
3. Orbits Signals and Codes
4. Receiver design
5. A-GPS
6. Future
D-GPS High Accuracy
High Sensitivity

Instructors

Per Enge Stanford University

Frank van Diggelen Stanford University

GPS MOOC Registration: 24,000 people from 182 countries.

4

Gender & Age

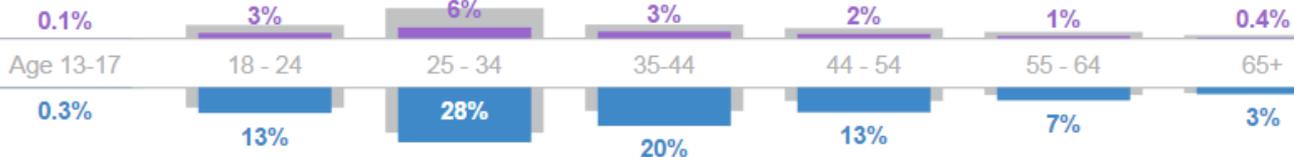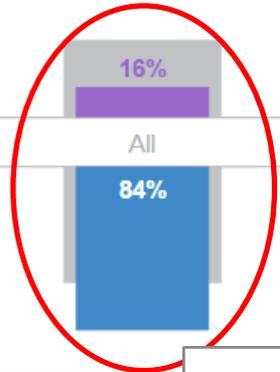**Your course**
- ■ Female (purple)
- ■ Male (blue)

All Coursera
- ■ (gray)

	All	Age 13-17	18 - 24	25 - 34	35-44	44 - 54	55 - 64	65+
Female	16%	0.1%	3%	6%	3%	2%	1%	0.4%
Male	84%	0.3%	13%	28%	20%	13%	7%	3%

% Representation of Women in GPS MOOC, by birth decade

Decade of birth (x-axis: 1940, 1950, 1960, 1970, 1980, 1990, 2000, 2010)

y-axis: 0% to 30%
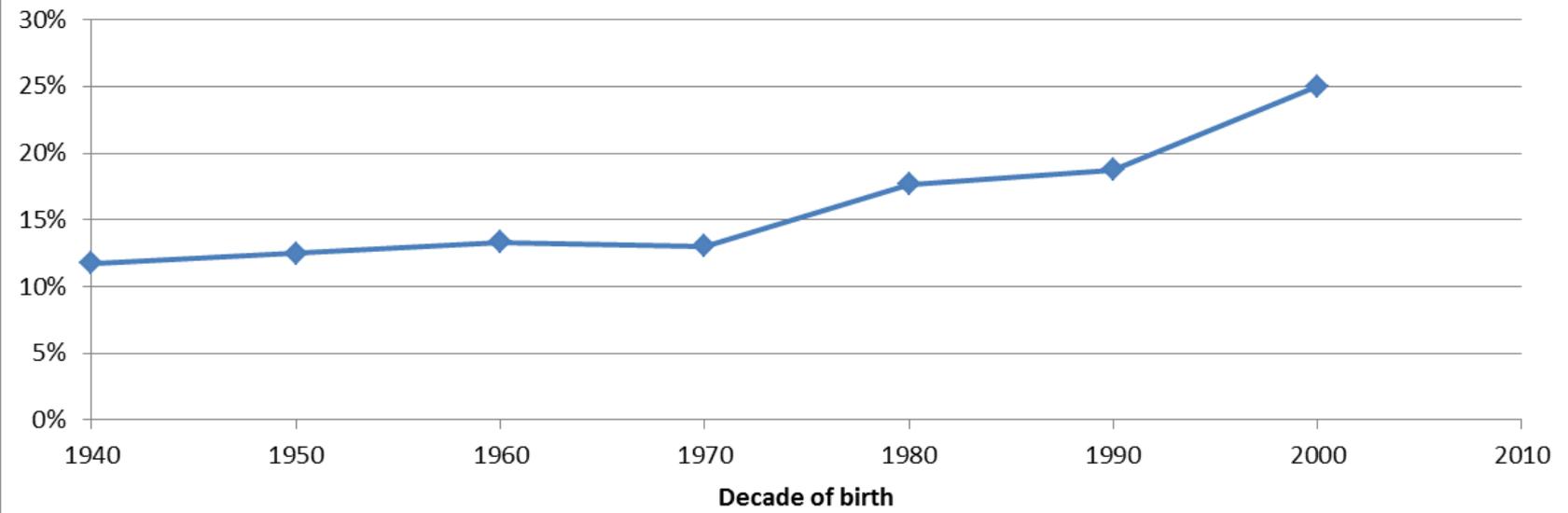
Labs, carried out worldwide, using smartphones

Stanford
GPS MOOC

GPS Worldwide Lab A (multipath

First, in an open area away from buildings, you will record y
Then in another location, this time in a city or town, in a plac
new GPS position and again note the error.

All instructions are posted at: http://www.gps-lab.org/labs.h
in Quiz Format before you submit here.

* Required

What was the error when you took the GPS reading in an ope
Estimate the error, by comparing what your GPS shows in "map v

○ 0 - 2 meters
○ 2 - 5 meters
○ 5 - 10 meters
○ 10 - 20 meters
○ 20 - 50 meters
○ 50 - 100 meters
○ 100 - 200 meters
○ Over 200 meters

GPS Worldwide Lab B (satellite visibility)

Go outside when one of these two satellites passes close to your location, and
satellite elevation that you observe.

All instructions are posted at: www.gps-lab.org/labs.htm. Be sure to first subm
Format before you submit here.

* Required

Which GPS satellite did you see *
Pick one of the two specified in the lab (if you see

○ Satellite 4
○ Satellite 18

Highest observed elevation for this satellite, t

○ 90
○ 80
○ 70
○ 60
○ 50
○ 40
○ 30 or lower

Your Latitude *
Enter degrees and decimals (e.g. 37.893), excludi

GPS Worldwide Lab C (signal strength)

Measure C/No value outside, and indoors. Estimate the RF losses of your
losses through the building.

All instructions are posted at: www.gps-lab.org/labs.html. Be sure to first
Quiz Format before you submit here.

* Required

Enter the average C/No value of the strongest three satellites, outdoors (U
See the lab instructions for help

**Compute the RF losses, compared to our nominal design (Units: dB). This
lab description. ***
x = 45 - (average outdoor C/No entered above)

Enter the average C/No value of the strongest three satellites, indoors (Un
If your receiver does not track three satellites, enter zero

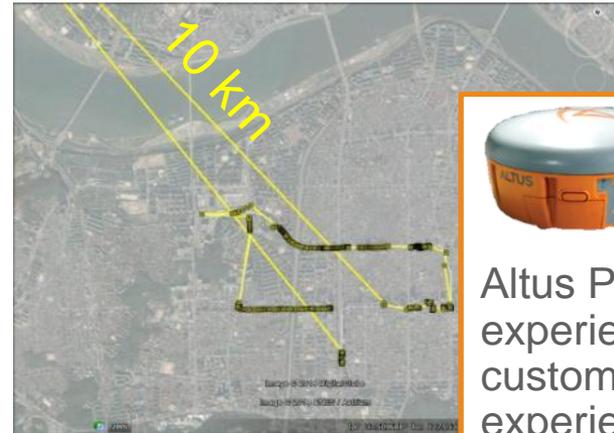# HOW GLONASS FAILED FOR 11 HOURS
AND MULTI-GNSS SURVIVED

Frank van Diggelen,
Stanford PNT
29 Oct 2014

Errors to 10km

2 APRIL 2014,
GPS/GLONASS RECEIVER:

True Path

Seoul, S. Korea

Image © 2014 CNES / Astrium

Google earth

lat 37.497671° lon 127.005912° elev   52 m   eye alt   4.31 km

Seoul, S. Korea, GPS/GLONASS

Altus Positioning: "we are experiencing calls from customers *all over the world*, experiencing GLONASS outages"

"all over the world", GPS/GLO receivers

```
HERS |98788876776557667677878*989888877887687775778879889988898888787767 99*89*
HERT |*98*998788867777667788889888888787877878777888989987988777787 88899*999
HLFX |66666677786678678777787776666778787890978*98887655666665877878987-----22-1
HNPT |866666667767878779888879766677667798998**99998666667677887899889 99*88888
HOB2 |889888799978988877768778887888799867888776666666677799879896787 7766667667
HOFN |9***9999*9989987887998999999999999*98***9998*87988999*999**98*99----23335
-----+----------------+----------------+----------------+----------------+-----
     0               12               24
```

 # GLONASS satellites tracked by IGS receivers (from **CODE** analysis protocol of April 1). **Some receivers unaffected, some stopped tracking GLONASS after 9[h] p.m. (red line), some even stopped GPS tracking!**

Out of about 180 receivers used by **CODE, about 60 were severely affected!**
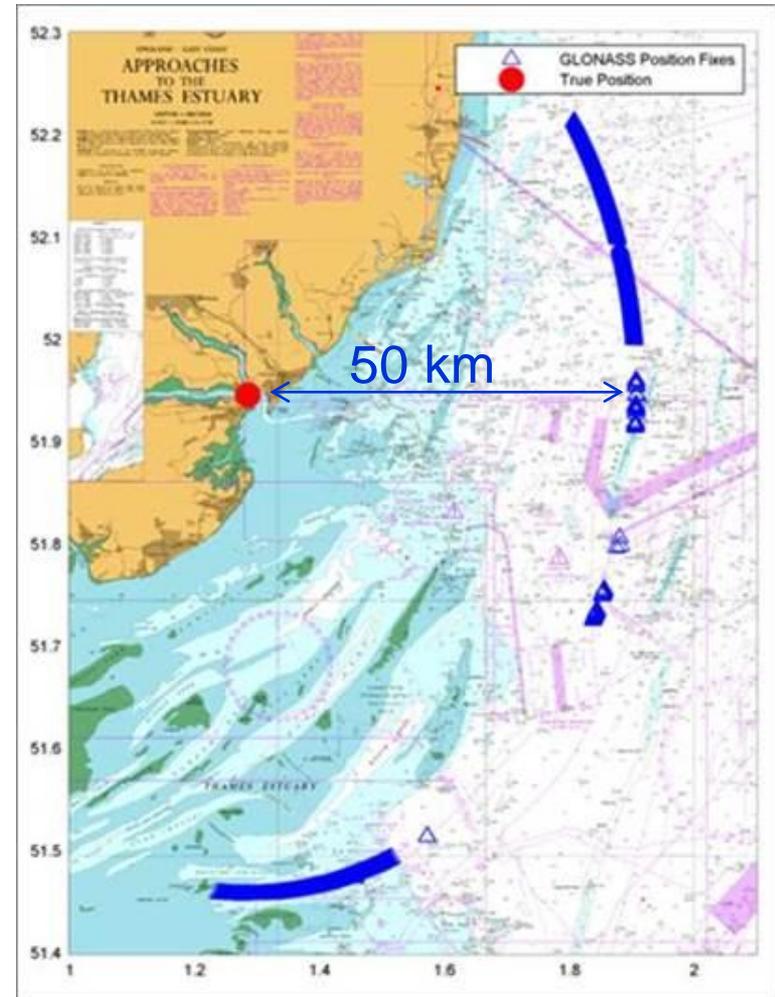
International Association of Geodesy

3-Jun-14   6

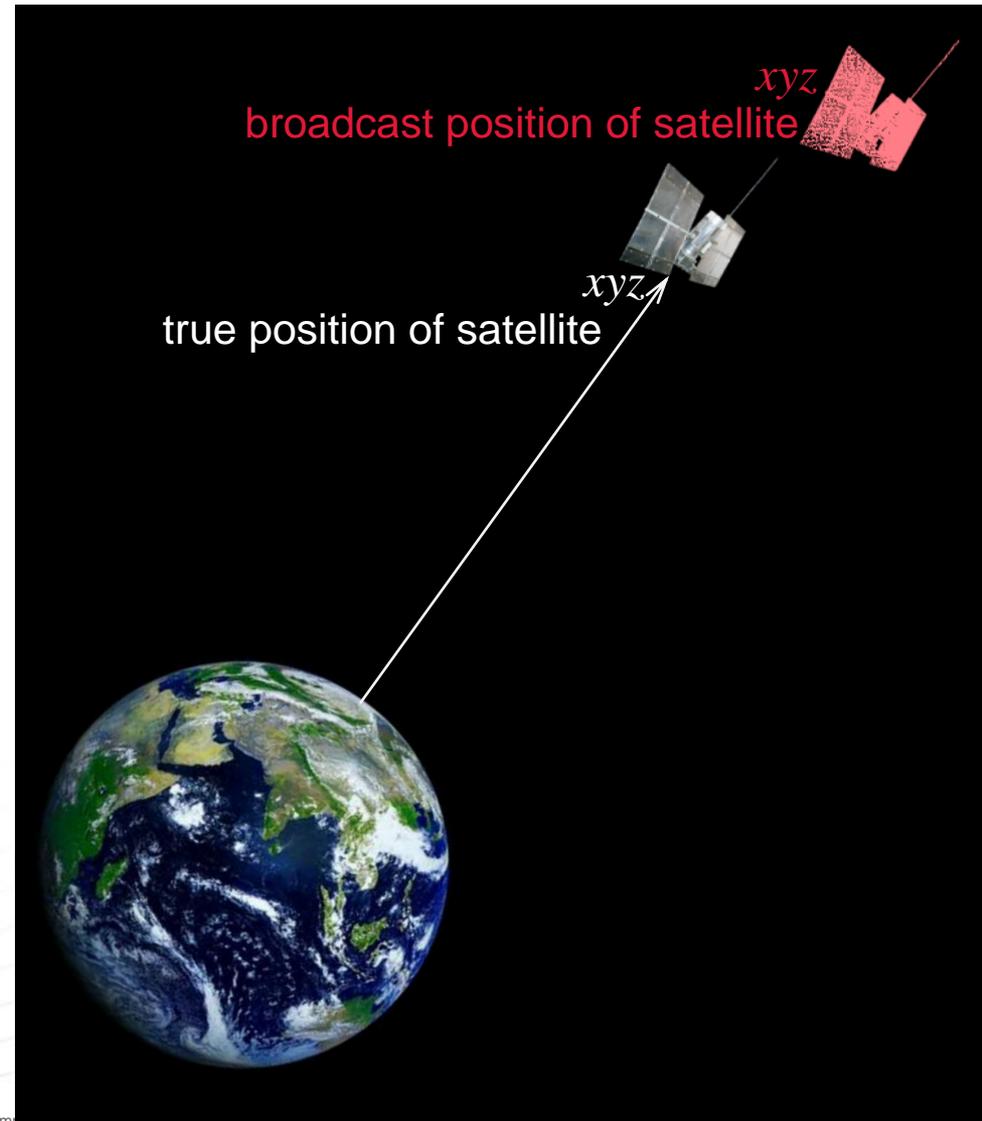IGS, Worldwide: "Of 180 receivers, 60 severely affected

Harwich, England, GLONASS receiver

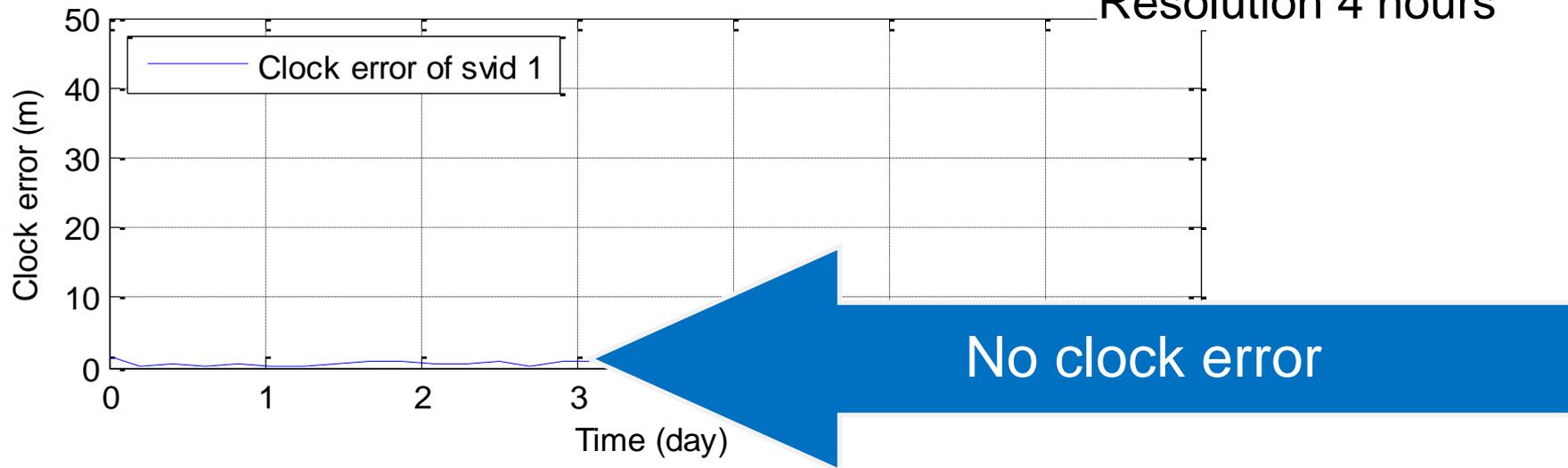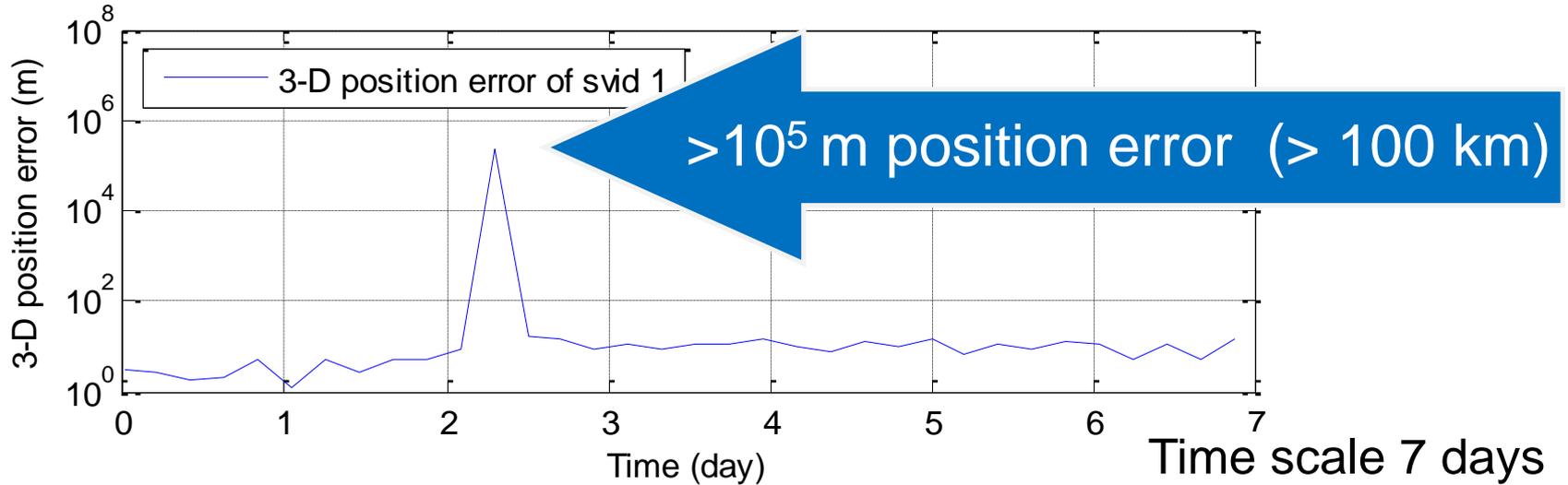1. Incorrect ephemeris uploaded to all GLONASS satellites:

xyz	× Bad
clock	✓ Good

2. No unhealthy flags set
3. Persisted for 11 hours

xyz
broadcast position of satellite

xyz
true position of satellite

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BROADCAST EPHEMERIS (BE) VS LTO

- **LTO = Long Term Orbits**
  - for GPS, GLO, QZS, BDS, GAL

- **Broadcom operates a worldwide reference network**
  - live tracking of all satellites all the time

- **After the GLONASS incident, we compared the collected BE against the previously predicted LTO ...**
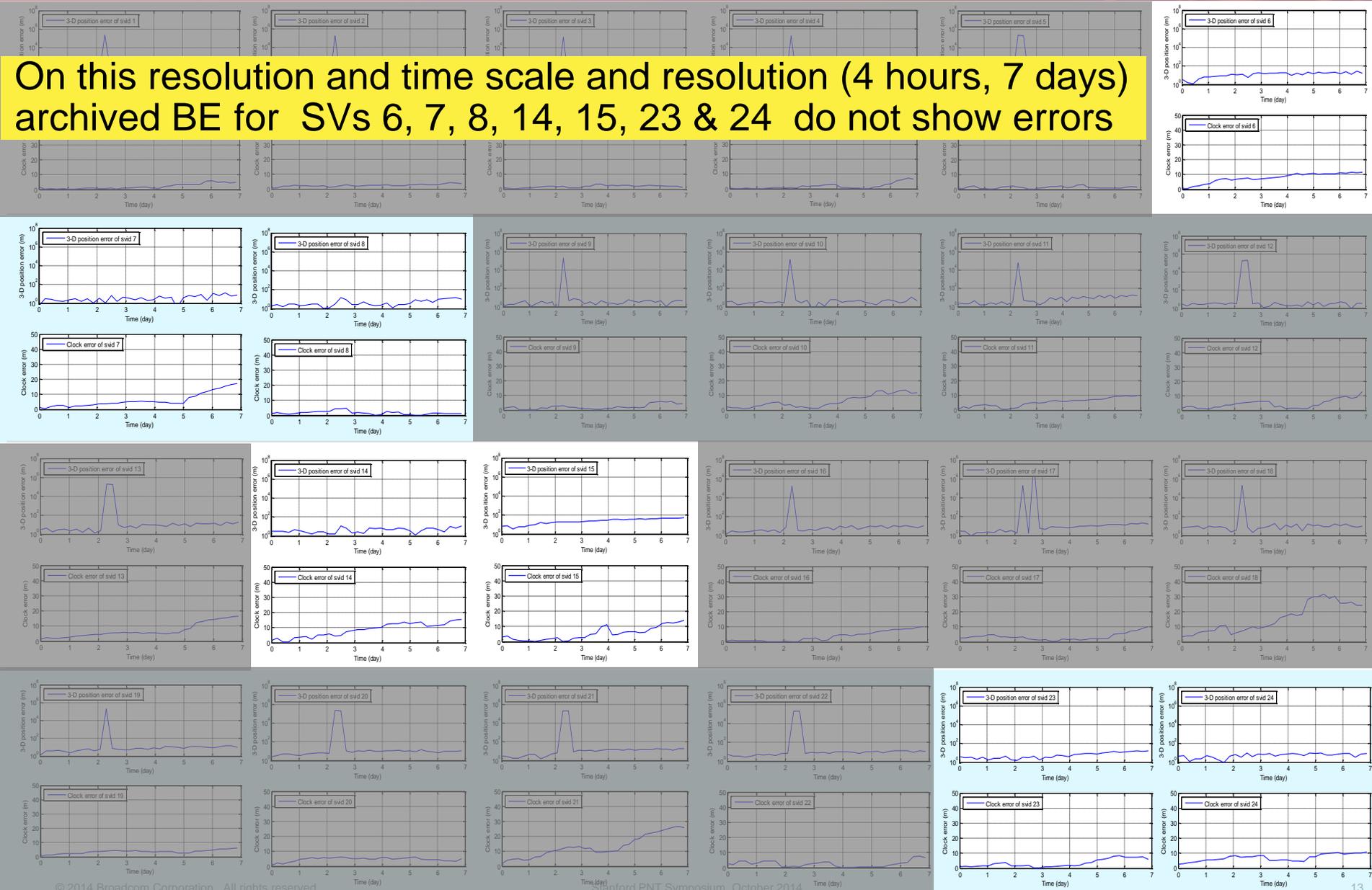
BE vs LTO, orbit and clock

>10^5 m position error (> 100 km)
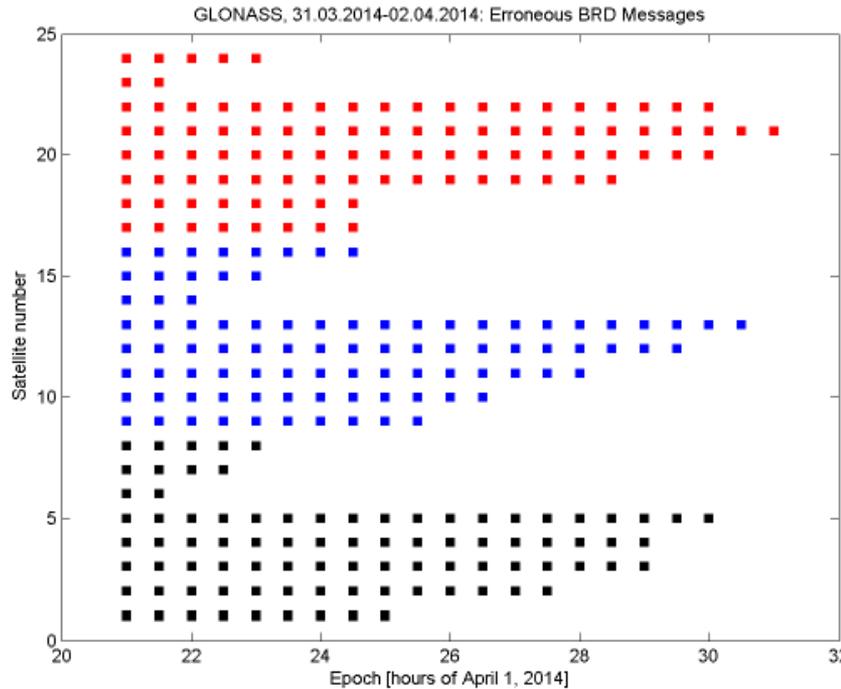
Time scale 7 days
Resolution 4 hours

No clock error

On this resolution and time scale and resolution (4 hours, 7 days) archived BE for SVs 6, 7, 8, 14, 15, 23 & 24 do not show errors

Stanford PNT Symposium, October 2014

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The GLONASS April 1st Incident in the IGS

GLONASS, 31.03.2014-02.04.2014: Erroneous BRD Messages

Time scale 10 hours
Resolution ½ hour

Messages affected (from Hugentobler, E-mail April 4). Satellites 6, 7, 8, 14, 15, 23, 24 back to normal before end of April 1st (UTC).

International Association of Geodesy

3-Jun-14   12

Courtesy: Gerhardt Beutler, Astronomical Institute, University of Bern

Stanford PNT Symposium, October 2014   14

"There were some mathematical mistakes, but they have been corrected,"
Oleg Ostapenko, head of the Russian space agency Roscosmos, 24 April 2014

From IGS analysis:

"Erroneous GLONASS Broadcast positions show a consistent rotation of about 0.5 degrees about inertial x-axis."

Speculation ...

Maybe this species of bug?

```
#define ROUND(x) ((int) (double)x+0.5) )
```

http://en.ria.ru/russia/20140424/189350346/Glonass-Failure-Caused-by-Faulty-Software--Roscosmos.html

http://gpsworld.com/the-system-glonass-in-april-what-went-wrong/ (Beutler)

http://www.gps.gov/governance/advisory/meetings/2014-06/beutler1.pdf

HEALTH FLAGS

From Russian Federal Space Agency Information-Analytical Center website:

Состояние КА ГЛОНАСС с 21:23:00 01.04.14 по 21:23:00 02.04.14 UTC+4

Legend:
- SC is in working regime (green)
- There isn't ephemeris (white)
- "Unhealthy" flag in ephemeris (red)
- Error (URE > 75м) (magenta)
- "Unhealthy" flag in almanac (dark purple)
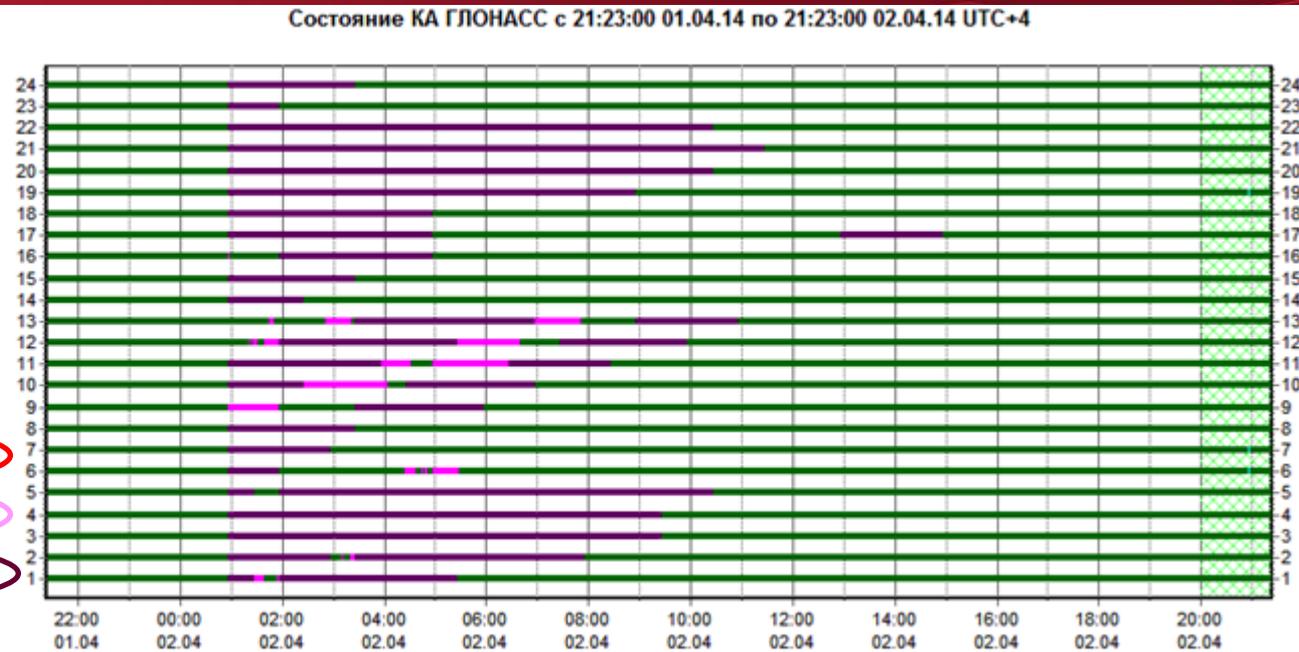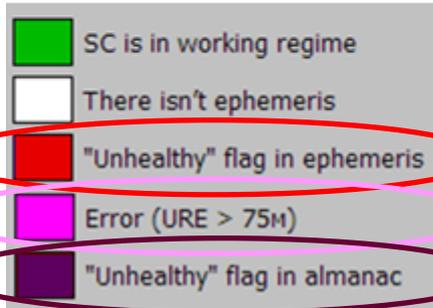
→ New almanac was not broadcast during this period
→ "Error (URE > 75м)" are observed error estimates, not broadcast URE
→ Unhealthy flag was never set on any of the satellites with bad ephemeris

From Broadcom Worldwide Reference Network, received ephemeris archive:

Health bits received from all GLONASS satellites throughout this time period.

No unhealthy flags.

Broadcast Ephemeris Health History of GLONASS during 21:15:00 01.04.14 – 21:15:00 02.04.14 UTC+4
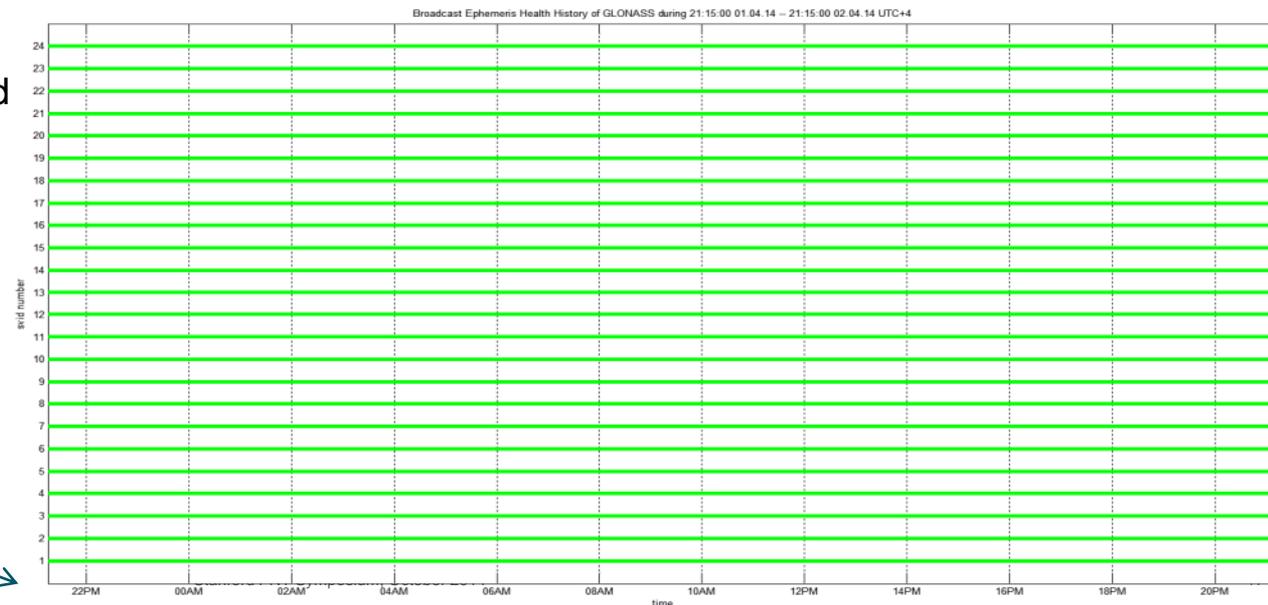
Time scale 24 hours

Resolution 15 minutes

The GLONASS April 1st Incident in the IGS

Source: http://www.gps.gov/governance/advisory/meetings/2014-06/beutler1.pdf

Broadcom database of all received broadcast almanac during this incident shows no almanac health bits set unhealthy at any time for any satellite.

```
select * from [WWRN].[dbo].[GlonassRawAlmanacArchive] where created > '2014-03-30 00:00:00' and created < '2014-04-02 23:30:00'
```

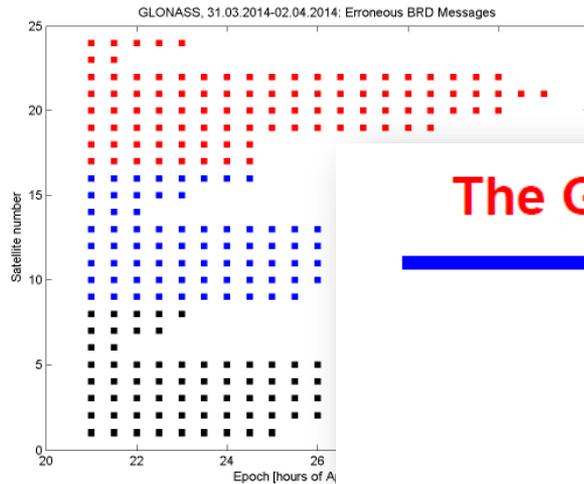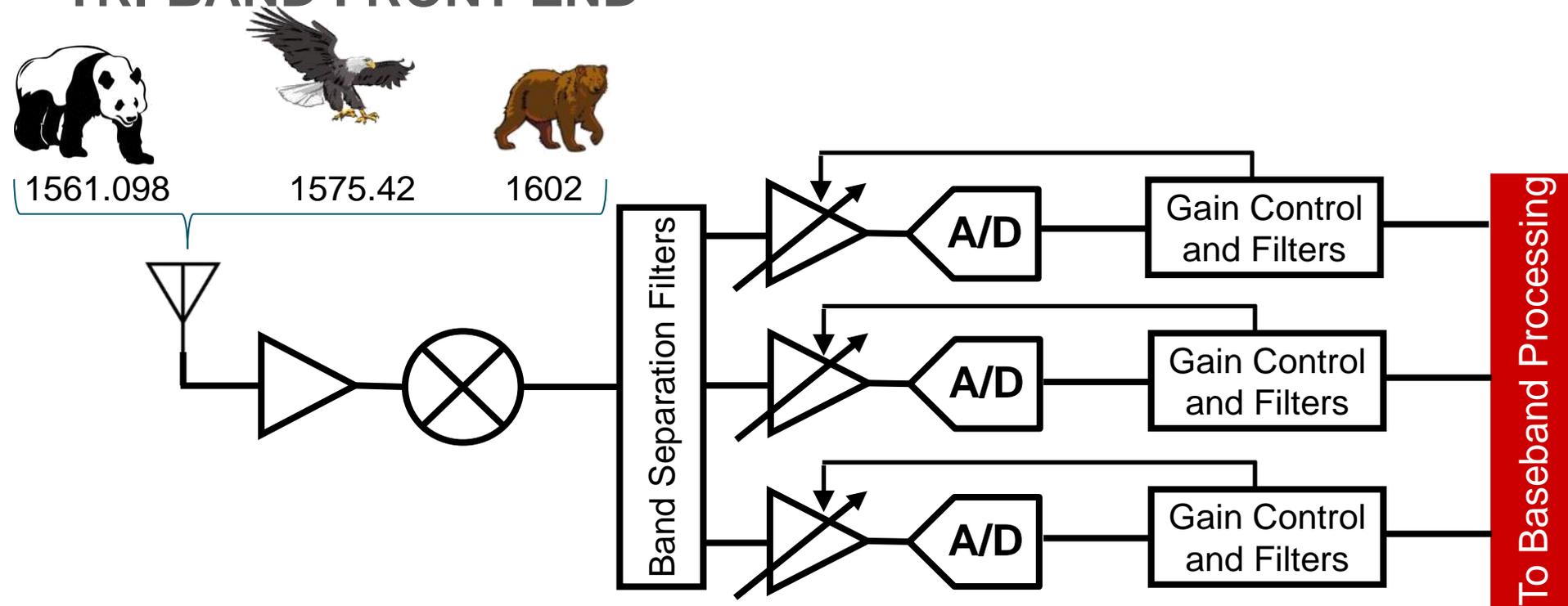|	created	tauGPS	N4	NA	nA2	HNA	lambdaNA	TLambdaNA	deltaINA	deltaTNA	deltaTDotNA	EpsilonnA	OmeganA	MNA	tauNA	CNA	Ln
1	2014-03-30 21:02:31.290	-428	5	821	1	1	55204	545286	7334	-1359814	-9	445	1656	1	43	1	0
2	2014-03-30 21:02:31.317	-428	5	821	2	28	-65541	703671	10077	-1359807	-9	1320	-20705	1	-17	1	0
3	2014-03-30 21:02:31.343	-428	5	821	3	5	-188542	867106	9099	-1359817	-9	1314	-19384	1	-3	1	0
4	2014-03-30 21:02:31.373	-428	5	821	4	6	-313999	1031251	9215	-1359800	-9	421	-18194	1	-17	1	0
5	2014-03-30 21:02:31.400	-428	5	821	5	1	-437171	1192158	7263	-1359835	-9	466	12169	1	42	1	0
6	2014-03-30 21:02:31.427	-428	5	821	6	28	422804	61606	7226	-1359780	-12	878	24568	1	-11	1	0
7	2014-03-30 21:02:31.453	-428	5	821	7	5	304353	219373	9145	-1359792	-13	1113	-19159	1	23	1	0
8	2014-03-30 21:02:31.480	-428	5	821	8	6	182640	379229	9188	-1359806	-9	1895	-13158	1	6	1	0
9	2014-03-30 21:02:31.510	-428	5	821	9	30	799642	491218	12334	-1359840	3	2607	3778	1	-2	1	0
10	2014-03-30 21:02:31.537	-428	5	821	10	25	680588	646110	16945	-1359807	3	1660	27419	1	4	1	0
11	2014-03-30 21:02:31.563	-428	5	821	11	0	554839	808909	14727	-1359816	3	2048	981	1	5	1	0
12	2014-03-30 21:02:31.593	-428	5	821	12	31	430751	976251	12320	-1359834	3	3491	29227	1	11	1	0
13	2014-03-30 21:02:31.620	-428	5	821	13	30	302529	1140379	14652	-1359807	3	786	14921	1	113	1	0
14	2014-03-30 21:02:31.660	-428	5	821	14	25	-927249	2403	16861	-1359709	1	1614	27077	1	0	1	0
15	2014-03-30 21:02:31.690	-428	5	821	15	0	1045838	165446	16850	-1360002	3	2497	-629	1	-4	1	0
16	2014-03-30 21:02:31.717	-428	5	821	16	31	919375	333450	12227	-1359796	3	2155	25590	1	-4	1	0
17	2014-03-30 21:02:31.743	-428	5	821	17	4	-552849	431498	11232	-1359921	0	1337	-21068	1	-28	1	0
18	2014-03-30 21:02:31.773	-428	5	821	18	26	-541928	423817	11644	-1360472	3	1826	-1626	1	8	1	0

... continues for 72 rows and 24 hours

TRI-BAND FRONT END

1561.098   1575.42   1602

Band Separation Filters

A/D — Gain Control and Filters

A/D — Gain Control and Filters

A/D — Gain Control and Filters

To Baseband Processing

Three independent system, if one system goes bad, it is easy to identify.

GLONASS Satellites isolated, not used

BeiDou Satellites used in good solution

P272 - UTC 02/04/2014 02:56:37.0

SV Count: 18 EA: 8m HDOP: 1.1 VDOP: 2.0

	GPS									SBAS		ГЛНС							OZSS北斗									
ALM ID	12	14	15	18	21	22	24	25	26	129	137	1	2	8	10	11	12	13	1	1	3	4	6	7	9	10	13	14
SVID	12	14	15	18	21	22	24	25	26	42	50	60	55	65	52	59	58	57	66	81	83	84	86	87	89	90	93	94
EL	33	25	36	81	25	45	65	13	0	44	43	72	39	24	12	65	54	2	42	45	42	34	75	65	71	38	1	51
AZ	140	285	78	263	217	309	44	173	84	159	152	69	328	123	30	34	205	209	181	159	205	133	163	234	304	232	314	313
dBHz	27	20	27	21	21	30	38	18	--	--	--	35	--	25	--	--	--	--	27	27	--	24	21	31	27	23	--	24

course=69° speed=30.7 km/hr

latitude=37.49929°, longitude=127.03231°, altitude=55m

TOOL ver. Wed Jan 29 16:38:17 PST 2014, © Broadcom

GLONASS Satellites used in bad solution

P132 - UTC 02/04/2014 02:54:13.0

SV Count: 6 EA: 11m HDOP: 1.1 VDOP: 0.9

	GPS									SBAS		ГЛНС							
ALM ID	12	14	15	18	21	22	24	25	26	128	12	1	2	8	10	11	12	13
SVID	12	14	15	18	21	22	24	25	26	41	4	60	55	65	52	59	58	57
EL	30	23	35	79	24	42	64	11	--	--	--	71	37	24	11	65	52	1
AZ	139	282	75	270	217	307	43	172	--	--	--	63	327	120	29	35	203	208
dBHz	30	32	35	25	23	36	20	13	--	31	30	25	38	28	21	25	25	--

course=24° speed=0 km/hr

latitude=37.49313°, longitude=127.03026°, altitude=88m

Image © 2014 CNES / A

UTC Time : May 20, 2014 3:03:13 AM
Lat : 53.08077750
Lon : 171.69181212
Alt : 10694.39 m
In Use : 16
In View : 16
Accuracy : 6.0 m
Speed : 956.45 km/h
Bearing : 267.31845
TTFF : 9.30 sec.
Elapsed Time : 01:22

UTC Time : May 20, 2014 4:42:00 AM
Lat : 46.13707304
Lon : 154.68443713
Alt : 10681.77 m
In Use : 18
Accuracy : 6.0 m
Speed : 855.08 km/h
Bearing : 229.64496
TTFF : 17.80 sec.
Elapsed Time : 00:32

UTC Time : May 21, 2014 1:10:38 PM
Lat : 32.06149548
Lon : 118.77931692
Alt : 20.80 m
In Use : 24
In View : 28
Accuracy : 8.0 m
Speed : 0.00 km/h
Bearing : 0.0
TTFF : 0.95 sec.
Elapsed Time : 00:11

8, 2014 5:30:54 PM
06732
248629
Accuracy : 8.0 m
Speed : 0.00 km/h
Bearing : 0.0
TTFF : 62.86 sec.
Elapsed Time : 17:35

4 BDS

6 BDS

9 BDS

2 BDS

Availability of 4 or more BeiDou satellites, above 10° horizon mask angle
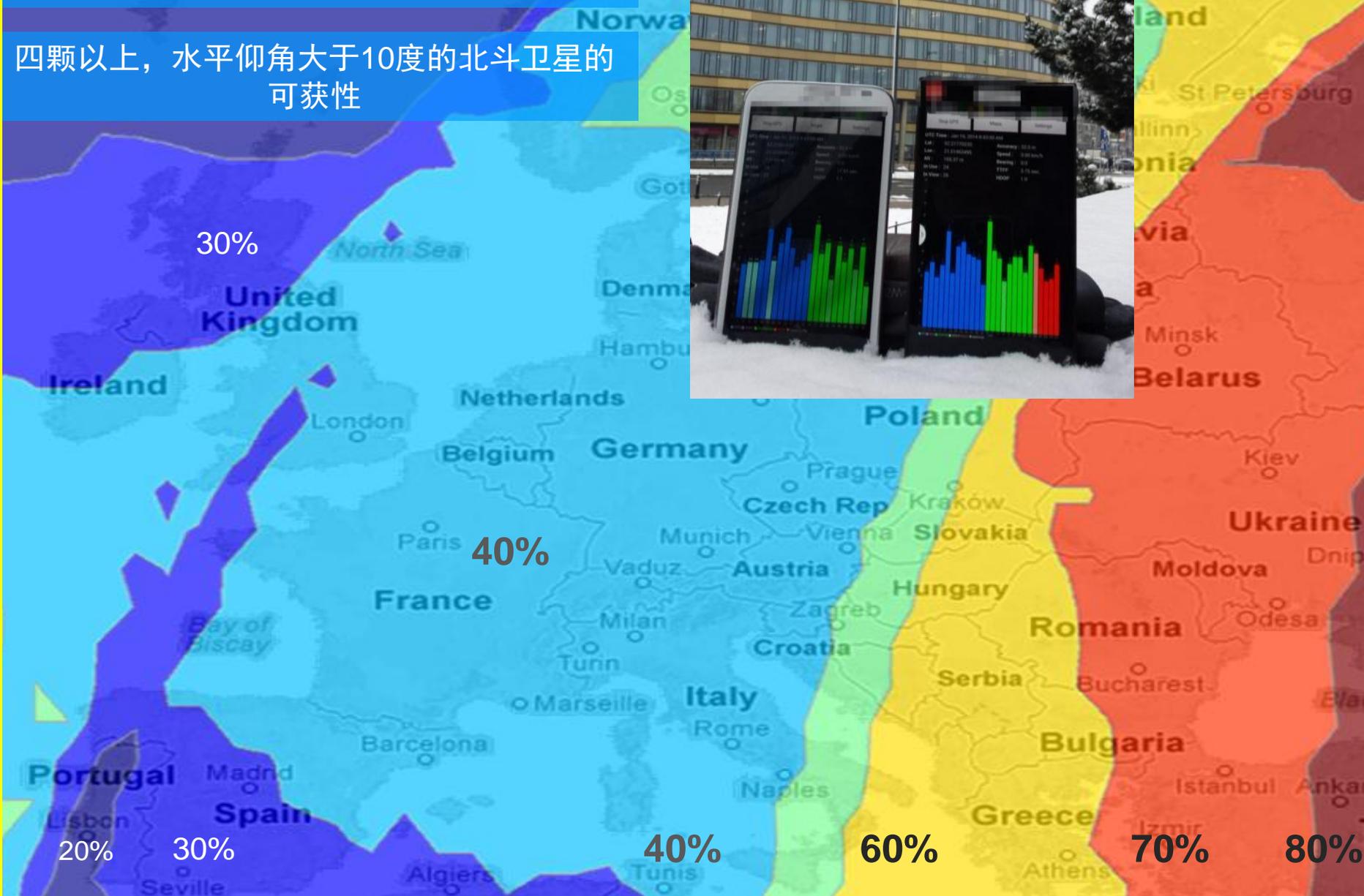
四颗以上，水平仰角大于10度的北斗卫星的可获性

40%

100%

50%
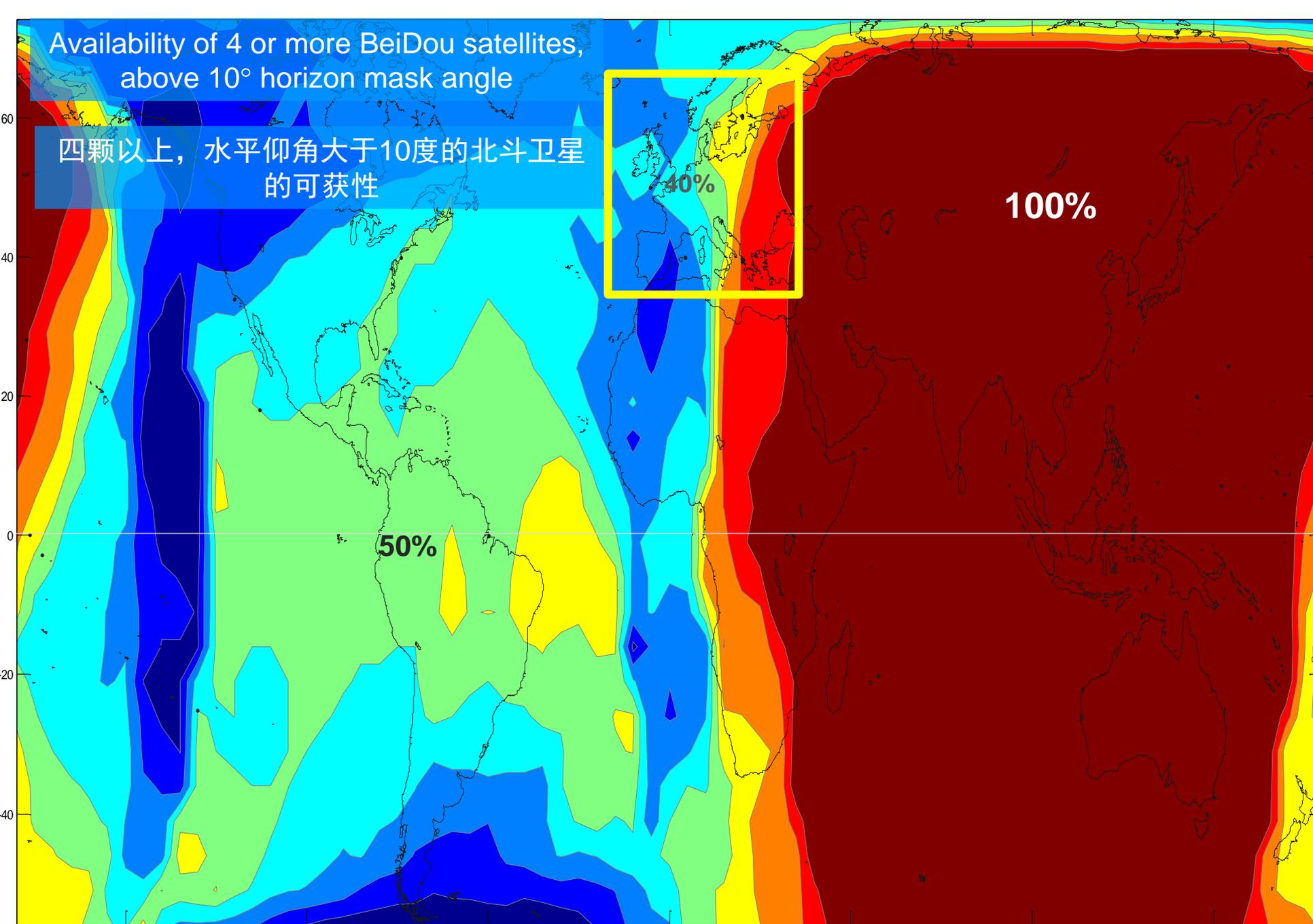
Availability of 4 or more BeiDou satellites, above 10° horizon mask angle
17 May 2013

四颗以上，水平仰角大于10度的北斗卫星的可获性

SUMMARY

- **GLONASS failure was caused by wrong Broadcast Ephemeris**

- **It affected all satellite orbits (but not clocks)**

- **IGS identified the error as an erroneous rotation of the orbital planes about the inertial x-axis**

  o **Error identified almost immediately by the GLONASS operators ...**

  o **... but not communicated to users through broadcast health bits in broadcast ephemeris or broadcast almanac**

  o **Commercial consumer LTO system (Broadcom) and Scientific system (IGS) show consistent data w.r.t duration and magnitude of errors and broadcast health bits**

- ✓ **Consumer products with GPS, GLONASS, QZSS and BeiDou operated seamlessly through the incident.**

- ✓ **With the addition of Galileo, this kind of robustness will be possible worldwide.**