GLONASS and Multi-GNSS in the IGS: Lessons learned from GLONASS Service Disruptions

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- The IGS as a multi-GNSS Service
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The International GNSS Service (IGS)

... is the **premier source of the highest-quality GNSS** data, products, and related standards and conventions

... is in **support of many applications** that benefit the scientific community and society

… is a **Service of the International Association of Geodesy** (IAG) founded in 1994

… is operational since more than 20 years

… is a **federation of more than 200 institutions** and organizations **worldwide**

… is following an **open data policy**

… is **open to everybody** to participate

The International GNSS Service (IGS)

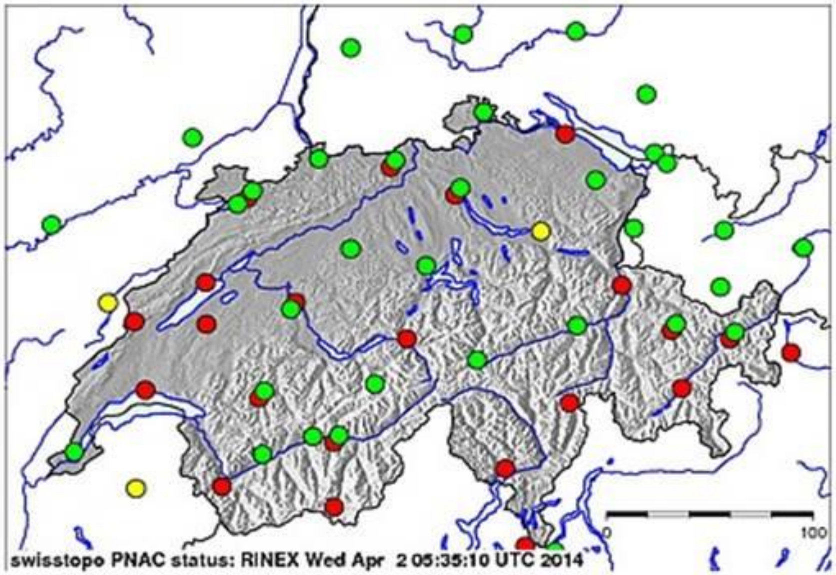
The IGS in particular operates

- **The MGEX, Multi-GNSS Experiment**
- **The IGS Real-time Experiment**

More about the two IGS entities will be presented tomorrow.

The GLONASS April 1st Incident: a case study

RINEX status in Switzerland 02-Apr-2014 07:35:22 (DOY 092)



Select region

Europe
Switzerland

PNAC status by subject

RINEX
NRT-Meteo
Coordinate Monitoring

Details

Prcocecssing swipos

Legend

- No data
- data o.k.
- 3<5 h miss./last h late
- > 5 h missing

RINEX status by site

AIGE	AND2	ARDE	ARD2	BLFT	BOUR	BOU2	BSCN	COMO	DAVO
DAV2	EPFL	ERDE	ETHZ	ETH2	FALE	FHBB	FLDK	FREI	FRIC
FRI3	HABG	HOHT	HOH2	HUTT	JUJO	KALT	KOPS	KRBG	KREU
LECH	LIND	LOMO	LUZE	MABZ	MARG	MAR2	MTTI	NEUC	PAYE
PFA2	PRNY	SAAN	SAA2	SAME	SANB	SAR2	SCHA	SIGM	STA2
STCX	STGA	VARE	VISW	WEIN	ZERM	ZIMM	ZIM2		

International Association of Geodesy

The GLONASS April 1st Incident in the IGS

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GODZ |566645667656777788888888666667566775898879*899886566654667767888899888874
GOLD |886688755544567557888789888788776566665588989888887777776666666677666788
GOPE |888799866665467656678777887877665566467766767777676888656655678 1----2224
GRAS |988988866567544664356665675888855666566766667678778877745666467775566788
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GUAM |876665655556544677676565776776765556545466575445565544545556645577776666
GUAT |7666666345556777887888876765555655567788989***988886666666677899 98888887
GUUG |888766655666688778889999889877776666787667779898877655555666689778-89999
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HERS |98788876776557667677878*988988877887687775778879889988898888787 76799*89*
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HLFX |666666777866786787777877766667787878997 8*988876556666587787898 7-----22-1
HNPT |86666666776787877988888797666776677989988**999988666667677889989 9*888888
HOB2 |889888799978988877768778887888799867888776666666677799879896787 7766667667
HOFN |9***9999*99899878879989999999999*98***9998*87988999*999**98*99----23335
-----+-----------------+-----------------+-----------------+-----------------+
     0                                   12                                 24
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 # GLONASS satellites tracked by IGS receivers (from CODE analysis protocol of April 1). Some receivers unaffected, some stopped tracking GLONASS after 9h p.m. (red line), some even stopped GPS tracking!

Out of about 180 receivers used by CODE, about 60 were severely affected!

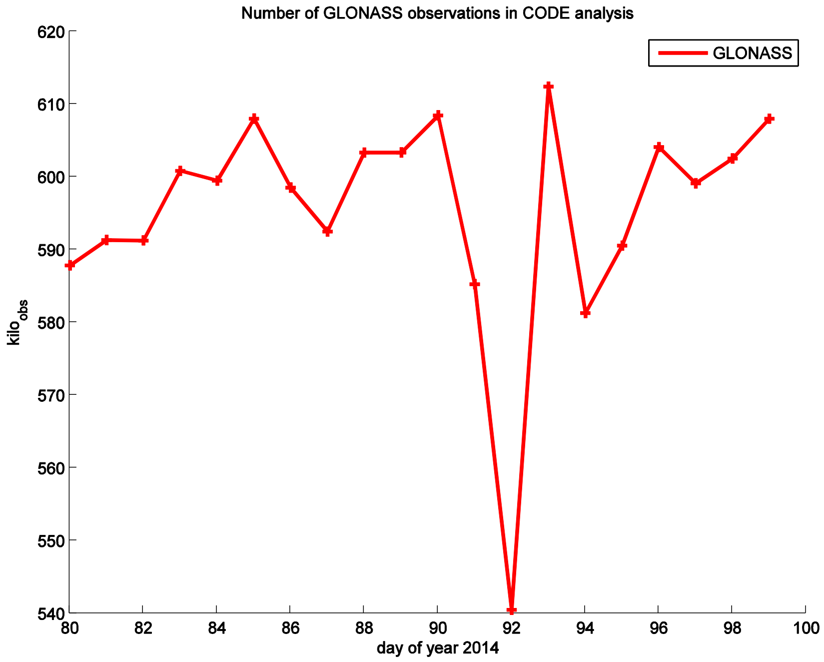
The International GNSS Service (IGS)

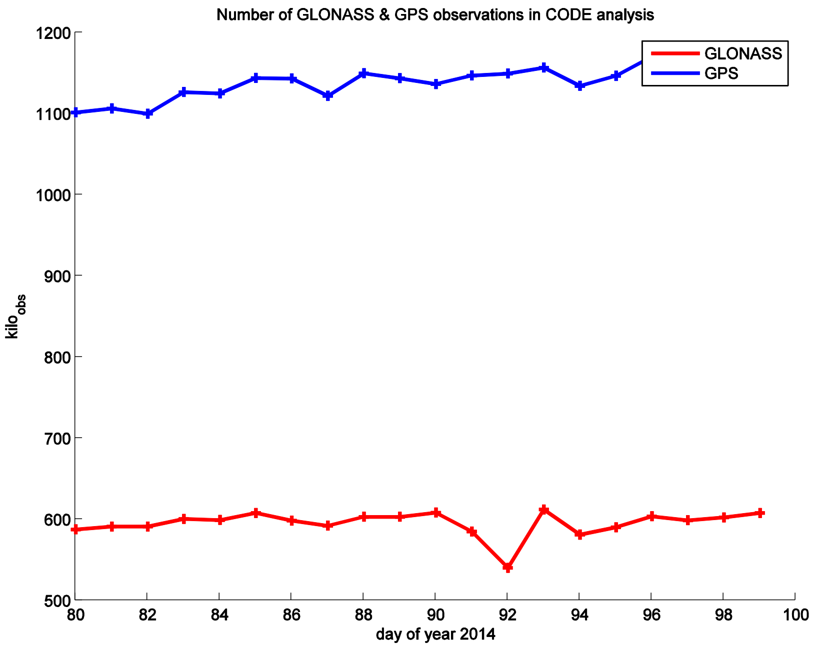
Site	City	Country	Lat	Lon	Height	Receiver	Antenna		Calibration	Last Data Avail	Satellite System
GODZ	Greenbelt	United States	39.02	-76.83	14.51	JPS EGGDT	AOAD/M_T	JPLA	N/A	24-May-14	GPS GLO
GOL2	Goldstone	United States	35.42	-116.89	986.68	ASHTECH UZ-12	AOAD/M_T	NONE	ROBOT	24-May-14	GPS
GOLD	Goldstone	United States	35.42	-116.89	986.68	JPS EGGDT	AOAD/M_T	NONE	ROBOT	24-May-14	GPS GLO
GOPE	Ondrejov	Czech Republic	49.91	14.79	592.60	TPS NETG3	TPSCR.G3	TPSH	ROBOT	24-May-14	GPS GLO
GOUG	Gough Island	dependent territory of the U.K.	-40.35	-9.88	81.27	LEICA GR10	LEIAR25	LEIT	ROBOT	N/A	GPS GLO GAL BDS
GRAC	Caussols	France	43.75	6.92	1319.80	TRIMBLE NETR9	TRM57971.00	NONE	ROBOT	N/A	GPS GLO GAL BDS SBAS
GRAS	Caussols	France	43.75	6.92	1319.30	TRIMBLE NETR5	ASH701945E_M	NONE	ROBOT	24-May-14	GPS GLO
GRAZ	Graz	Austria	47.07	15.49	538.30	LEICA GRX1200+GNSS	LEIAR25.R3	LEIT	ROBOT	24-May-14	GPS GLO
GUAM	Dededo	Guam	13.59	144.87	201.92	JAVAD TRE_G3TH DELTA	ASH701945B_M	JPLA	N/A	24-May-14	GPS GLO
GUAO	URUMQI	CHINA	43.47	87.18	2049.20	ASHTECH UZ-12	ASH701945B_M	NONE	COPIED	14-Apr-14	GPS
GUAT	Guatemala City	Guatemala	14.59	-90.52	1519.90	LEICA GRX1200GGPRO	LEIAR25.R3	LEIT	ROBOT	24-May-14	GPS GLO
GUUG	Mangilao	USA	13.43	144.80	134.70	TRIMBLE NETR5	TRM55971.00	NONE	ROBOT	24-May-14	GPS GLO
HALY	Halat Ammar	Saudi Arabia	29.14	36.10	861.68	TRIMBLE NETRS	ASH701945C_M	SCIT	FIELD	N/A	GPS
HARB	Pretoria	Republic of South Africa	-25.89	27.71	1555.00	TRIMBLE NETR9	TRM59800.00	NONE	ROBOT	24-May-14	GPS GLO GAL SBAS
HARV	Vandenberg AFB	United States	34.47	-120.68	14.97	JAVAD TRE_G3TH DELTA	AOAD/M_T	JPLA	N/A	15-Jan-14	GPS GLO
HERS	Hailsham	United Kingdom	50.87	0.34	76.50	SEPT POLARX3ETR	LEIAR25.R3	NONE	ROBOT	24-May-14	GPS GLO
HERT	Hailsham	United Kingdom	50.87	0.33	83.30	LEICA GRX1200GGPRO	LEIAT504GG	NONE	ROBOT	24-May-14	GPS GLO
HLFX	Halifax	Canada	44.68	-63.61	3.10	TPS NET-G3A	TPSCR.G3	NONE	ROBOT	24-May-14	GPS GLO

The GLONASS April 1st Incident in the IGS

Time (UTC)	Chronicle of Events
April 1, 21:00	GLONASS starts transmitting “infected” Broadcast messages simultaneously from all satellites.
April 2, 7:00	All GLONASS satellites transmit again correct broadcast messages (satellite 21 last satellite).
April 3, 9:23	E-Mail by Chris Rizos (IAG President and IGS GB member) to IGS GB et al: “What do you guys know about this? Have you been fielding any questions from media? users?” (wake-up call for IGS)
April 3, 10:36	E-Mail by Tim Springer (ESA Analysis Center) stating in essence that the “normal” IGS processing (final, rapid, ultra-rapid) was not affected (“nobody noticed”)
April 4, 14:29	E-mail by Urs Hugentobler, Chair IGS Governing Board : First IGS-internal analysis of the event. Osculating elements derived from GLONASS Broadcast analyzed. He “sees” rotations of orbital planes, specific to three GLONASS planes
Since	Various attempts to explain the signature of the event (from cyber war to more technical and resonable)

The GLONASS April 1st Incident in the IGS





From CODE Analysis protocol: Number of GLONASS observations reduced by about 10% on April 2nd. → this is why the IGS post-processing products were virtually not affected (orbits are based on one day of observations). Had the incident lasted for > 1 day, the impact would have been more severe.

The GLONASS April 1st Incident in the IGS

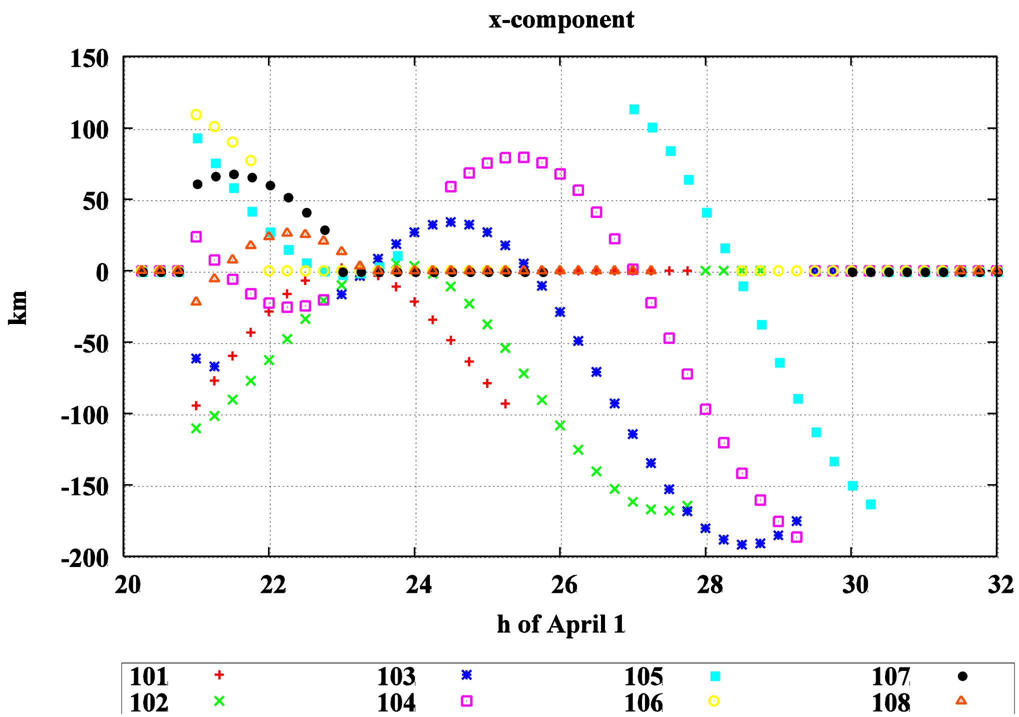
Satellite position differences in next slide

- **refer to the GLONASS/Broadcast- and CODE/IGS-derived positions ("truth").**
- **in the Earth-fixed equatorial system**
- **between April 1st, 20:00 and April 2nd, 08:00**

- **the differences are of the order of ± 200km**
- **between April 1st, 21:00 and April 2nd, 07:00**

- **Before April 1st, 21:00 and after April 2nd, 07:00 the differences are small, of the order of few meters.**

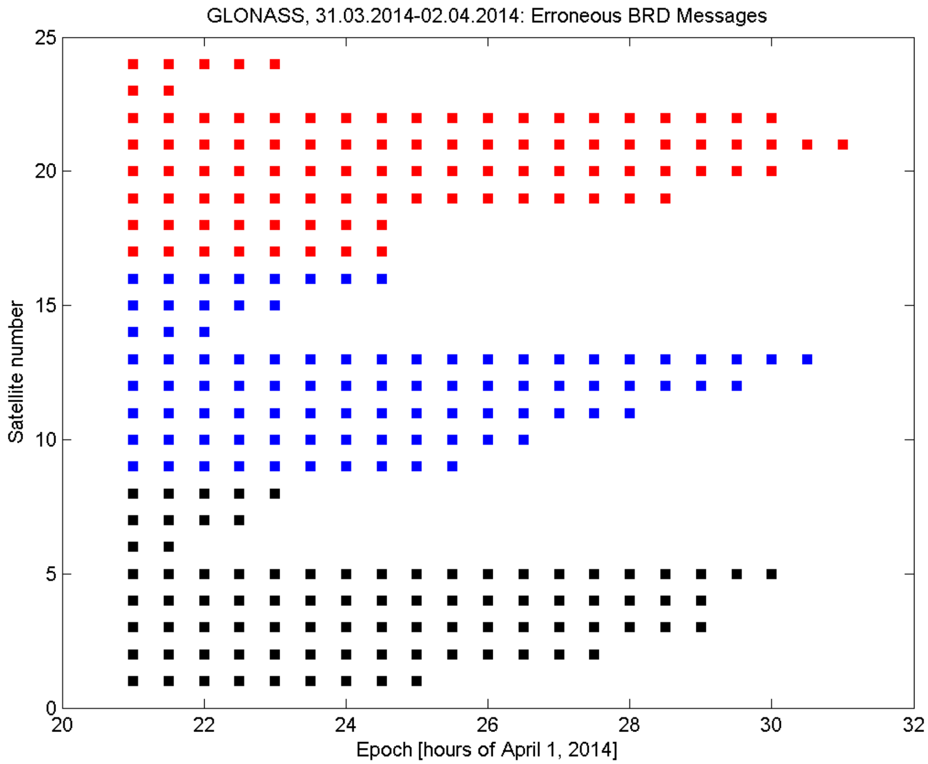
The GLONASS April 1st Incident in the IGS



Bad Broadcast Messages (resulting in satellite position errors up to about ±200km) were sent out starting April 1, 2014, 21h UT; Errors in geocentric, Earth-fixed x-coordinate of satellites of orbital plane 1.

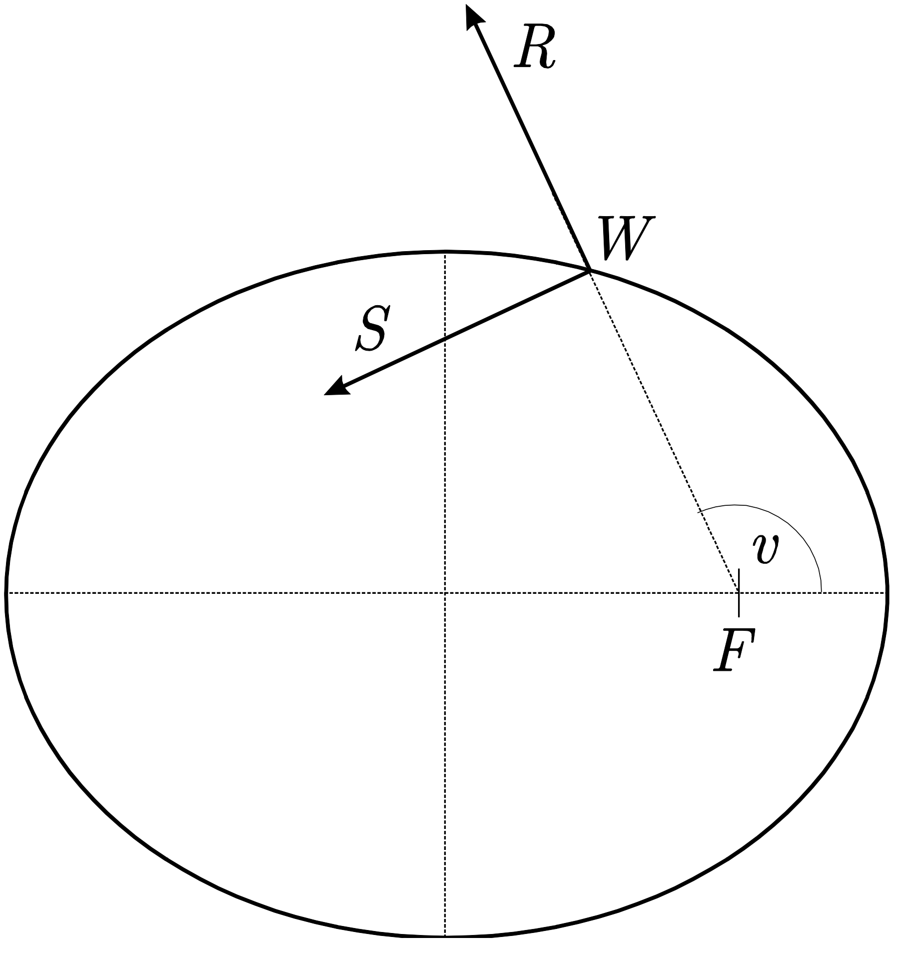
Normal transmission resumed at different times for different satellites. Complete "back to normal" around 7h UT of April 2.

The GLONASS April 1st Incident in the IGS



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).

The GLONASS April 1st Incident in the IGS



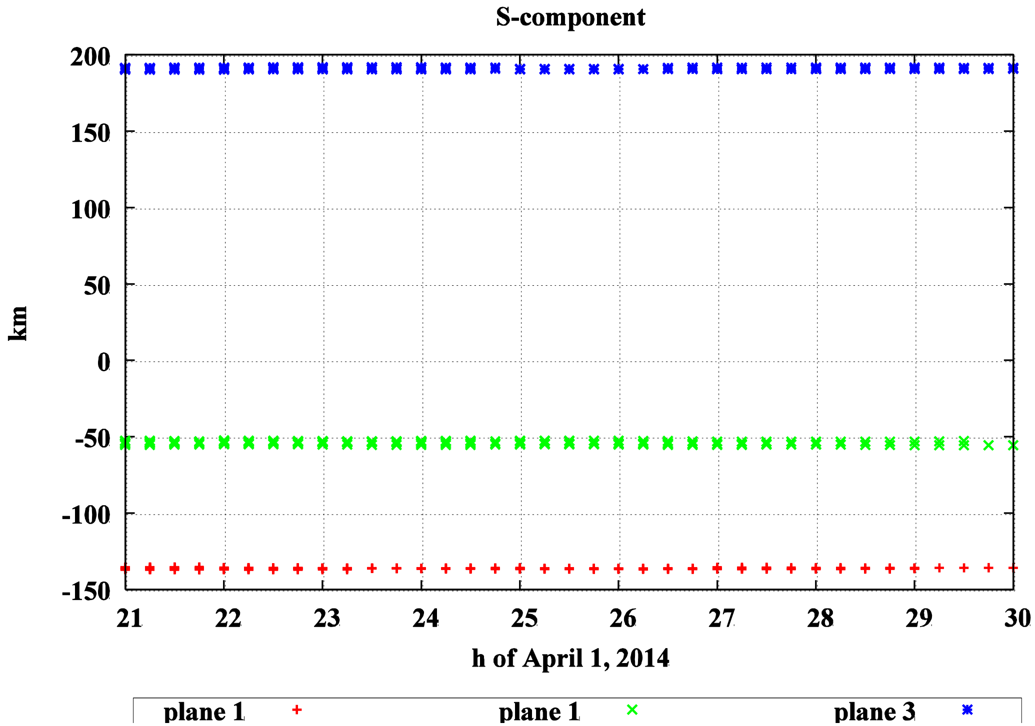
The (***R*,*S*,*W***) coordinate system gives more insight into the structure of the 3-d position differences.

For circular orbits the *S* component coincides with the along-track component.

The position differences

- **are small in *R* (sub-km),**
- **are sizeable and almost constant in *S* within the three orbital planes,**
- **are sizeable and satellite-specific in the out-of-plane direction.**

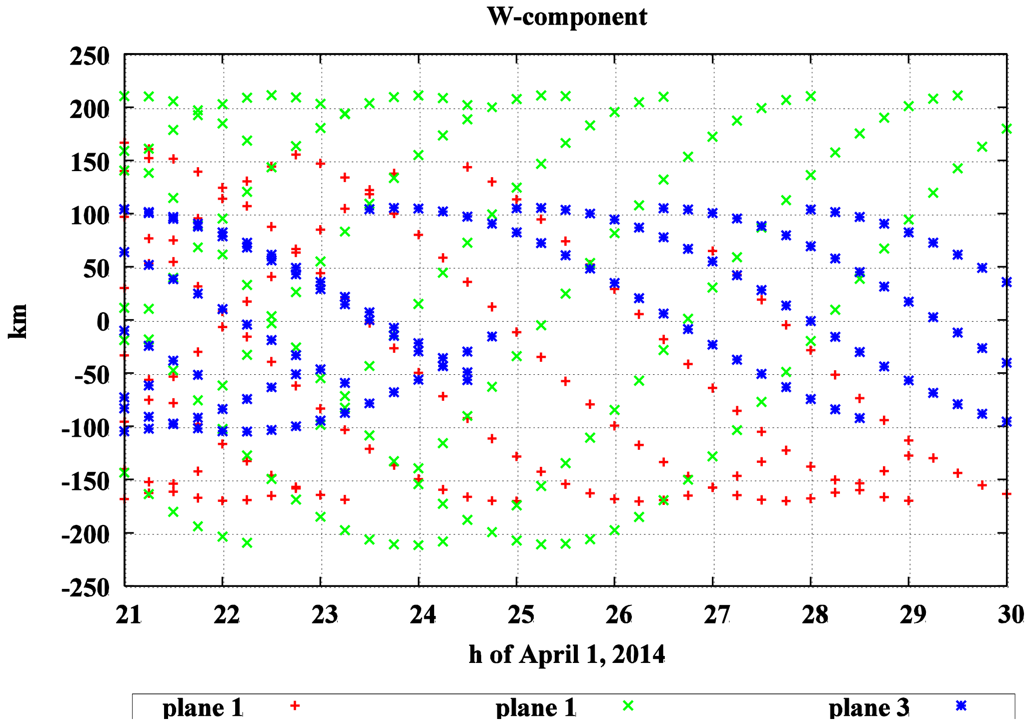
The GLONASS April 1st Incident in the IGS



Bad Broadcast Messages (resulting in position errors up to about ±200km) were sent out starting April 1, 2014, 21:00; Errors in along-track coordinate S of satellites in orbital planes 1, 2, 3 are almost constant within each orbital plane.

Normal transmission resumed at different times for different satellites. Back to normal around 7h UT of April 2.

The GLONASS April 1st Incident in the IGS



Bad Broadcast Messages (resulting in position errors up to about ±200km) were sent out starting April 1, 2014, 21:00; Errors in out-of-plane coordinate W of satellites in orbital planes 1, 2, 3 are satellite-specific and periodic with amplitudes of the order of up to 200 meters.

Normal transmission resumed at different times for different satellites. Back to normal around 7h UT of April 2.

The GLONASS April 1st Incident in the IGS

Three orbits using **satellite positions as pseudo-observations** were determined for each satellite:

- **F1_**: GLONASS Positions from CODE final processing. Time interval April 1 , 20^h00^m – April 2, 07^h00^m . Reference orbit ("truth").
- **GL_1**: Positions from GLONASS Broadcast Ephemerides. Time interval April 1, 0^h00^m – April 1, 20^h45^m . (Correct GLONASS Broadcast Orbit).
- **GL_2**: Positions from GLONASS Broadcast Ephemerides. Time interval April 1 , 21^h00^m – 23^h45^m. (Erroneous GLONASS Broadcast Orbit). Last observations of day skipped for satellites 6, 7, 8, 14, 15, 23, 24.

Each orbit was parameterized with 6 osculating elements (initial values) **and 9 empirical parameters** of the CODE model.

The GLONASS April 1st Incident in the IGS

Satellite	RMS (F1_)	RMS(GL-1)	RMS(GL-2)
1, plane 1	0.01	0.37	0.46
2 , plane 1	0.02	0.34	0.42
3 , plane 1	0.01	0.36	0.33
4 , plane 1	0.02	0.40	0.32
5 , plane 1	0.02	0.35	0.44
6 , plane 1	0.01	0.33	0.23
7 , plane 1	0.01	0.36	0.73
8 , plane 1	0.02	0.37	0.44

The GLONASS April 1st Incident in the IGS

The RMS values show:

- **F1_: The consistency of the 15-parameter solution with the more elaborate CODE orbit model.**
- **GL-1 and GL-2: the positions of both GLONASS-derived positions obey the laws of Celestial Mechanics.**
- **The GL-1 and GL-2 positions cannot be mixed in orbit determination!**

The GL-1 and GL-2 positions are compared to the F1_- positions by estimating three rotation angles about the equatorial inertial x-, y-, and z-axes.

The GLONASS April 1st Incident in the IGS

Solution	Rot x (“)	Rot y (“)	Rot z (“)	RMS (m)
GL-1	0.00	-0.00	0.38	2.0
GL-2	-1763.25	5.28	2.09	70.7

Rotation of GLONASS Broadcast Orbits w.r.t. CODE 1-d orbits F1_ .

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

The GLONASS April 1st Incident in the IGS

Understood:

- **The GNONASS April 1st event was *not* a joke.**
- **The failure was caused by wrong Broadcast Ephemerides**
- **… probably caused by a software update, activated on April 1st at 9h p.m. UTC (24h/0h "Moscow Time")**
- **The error was**
  - **identified by the GLONASS provider almost immediately after the activation of the new BE …**
  - **but not communicated to the users of GLONASS.**
- **The correction (switch back to "old" software release?) took place satellite-by-satellite (starting on April 1, 10h45m p.m. UT).**
- **The effect on receivers obviously was dependent on the receiver type & firmware release.**

The GLONASS April 1st Incident in the IGS

Aspects to be considered by the IGS:

- **The Broadcast Ephemerides (BE) are not needed for the IGS post-processing activities (ultra-rapid, rapid, final).**
  - → **No actions needed concerning BE for these applications**
  - → **Report about malfunctioning receivers might be collected routinely and made available in a report.**
- **The BE are, however, of vital importance for the IGS Real-time Service (corrections w.r.t. BE are sent out); the BE are a "single point of failure" for the IGS real-time Experiment.**
  - **Therefore one should either**
    - → implement an IGS real-time validation of all BE of all GNSS and make it available to the user community.
  - **or**
    - → reconsider the use of the BE for the IGS Real-time Experiment, as well.

The GLONASS April 1st Incident in the IGS

Aspects to be considered by the IGS (cont):

GPS and GLONASS are today fully deployed systems. Despite that fact only combined solutions (or GPS-only solutions) are generated in the IGS.

One might apply the following principle for fully deployed systems in the IGS:

- **Prior to combination, parameters of general interest (e.g., station coordinates, Earth Rotation Parameters) should be determined separately using only the observations of either GPS or GLONASS.**
- **GNSS-specific problems are more easily identified this way.**
- **The same principle should be observed by receiver software/firmware.**

In addition, the quality of BE of all GNSS should be monitored by the IGS. For that purpose the predicted part of the IGS ultra-rapid orbits might be used.

Back-up Slides

Multi-GNSS Experiment (MGEX)

Multi-GNSS Experiment (MGEX)

- **MGEX call-for-participation released mid-2011 (ongoing)**
- **Steered by Multi-GNSS Working Group (MGWG)**

Some 27 contributing agencies from 16 countries

Global tracking network, mostly real-time

- **State-of-the-art receivers and antenna**
- **Tracking of Galileo, BeiDou, QZSS, SBAS (but no IRNSS, yet)**

Free and open access

- **Data archives at CDDIS, IGN, BKG (RINEX 3.x)**
- **Real-time NTRIP caster (RTCM3-MSM)**
- **Product archive at CDDIS**

IGS Real-time GNSS Service

Bundesamt für Kartographie und Geodäsie

Open Data

- Observations & derived products freely available
- Streaming data over IP Networks in real-time
- Best effort operations, distributed governance
- Funded by national agencies, institutions, science
- Playing some global coordination role

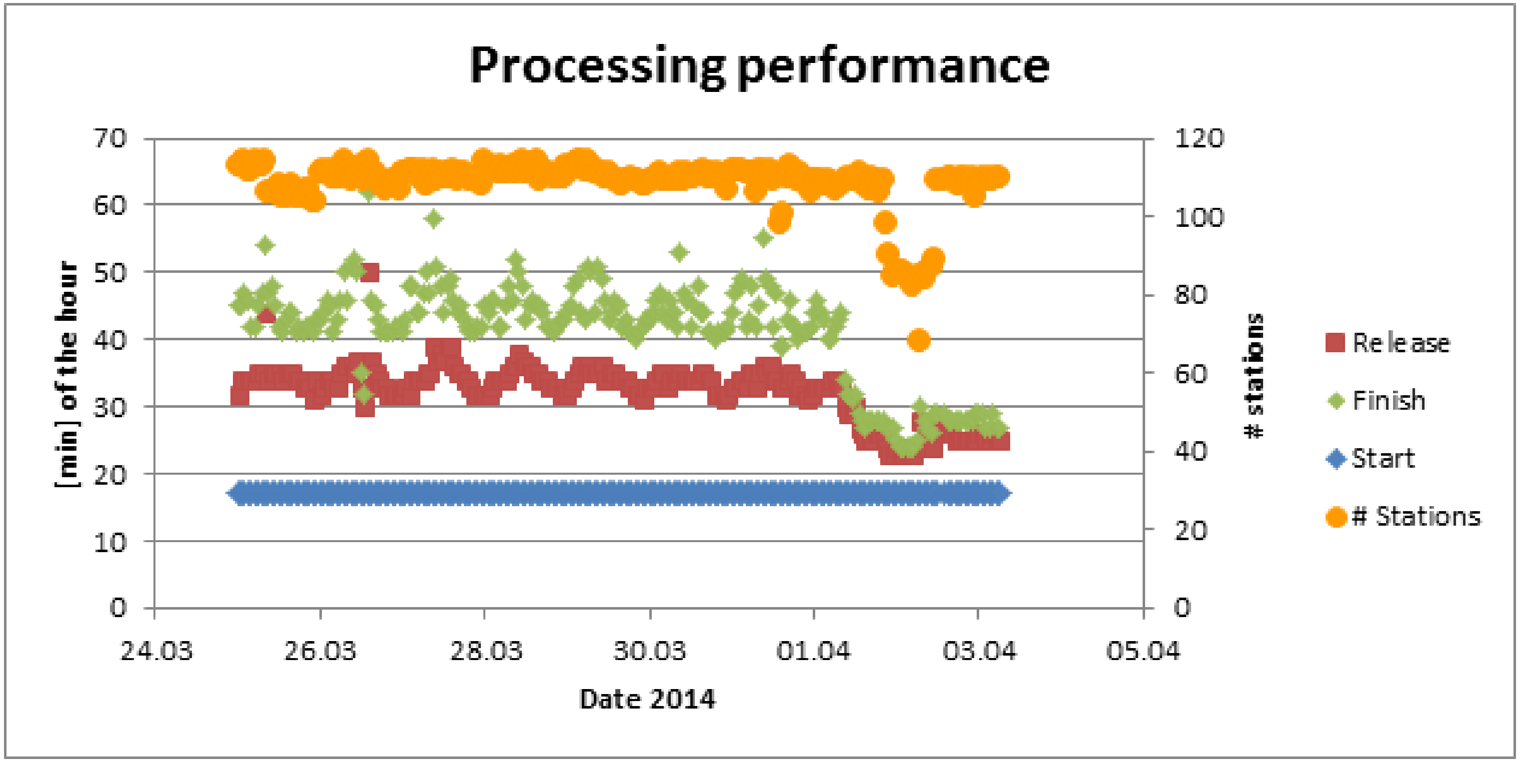
Open Source

- Supporting Real-time GNSS tools for Linux, Solaris, Window, Mac
- Multi-stream decoder, feeding GNSS engines, etc.
- Combining, encoding and uploading orbit/clock corrections
- Precise Point Positioning options
- Support of all GNSS through RINEX-3

Open Standards

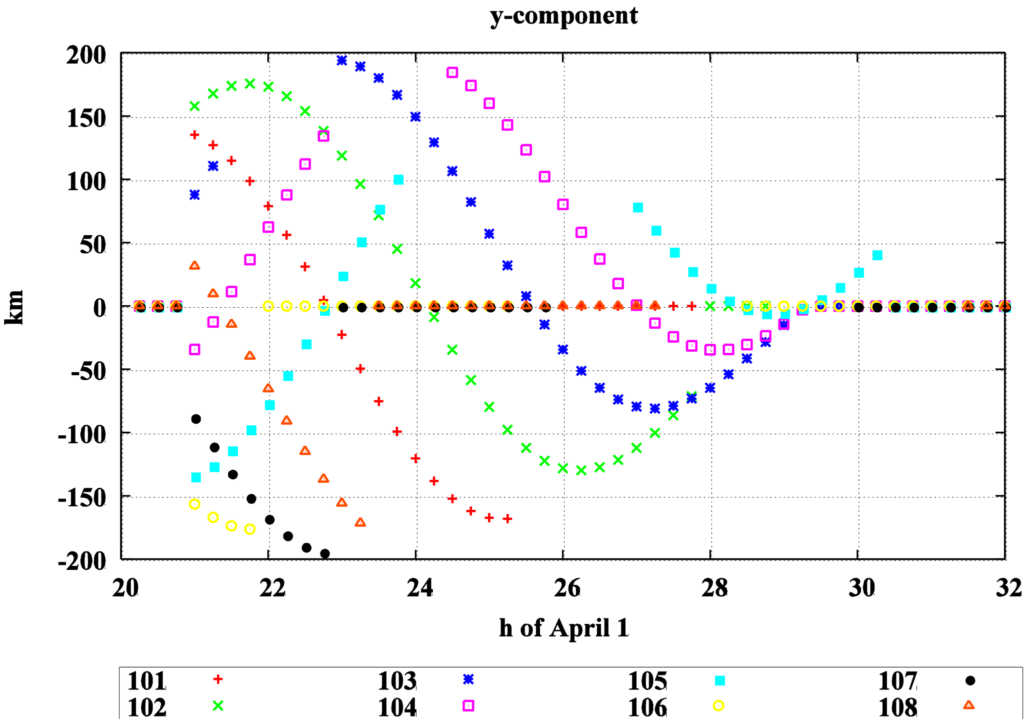
- Standardization in RTCM is understood as key issue
- Concepts and messages for all types of corrections
- Make PPP an optional alternative to Network RTK

The GLONASS April 1st Incident: a case study



AGNES network of Swisstopo (one receiver type). Impact was heavy! GPS tracking was affected, as well!

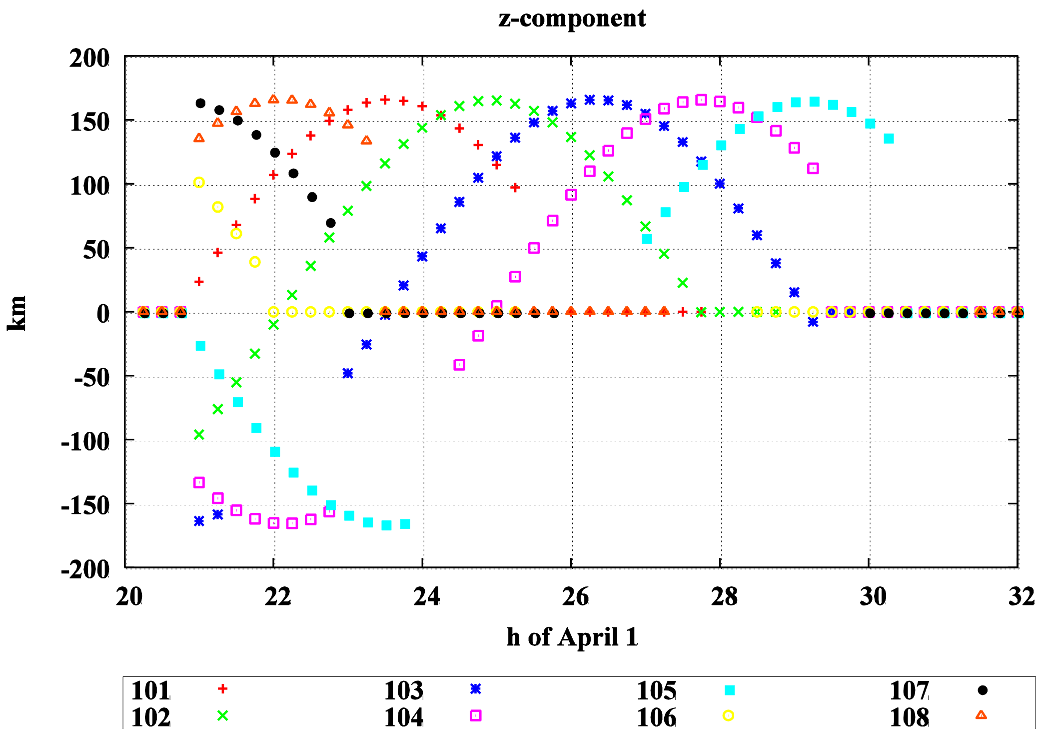
The GLONASS April 1st Incident



Bad Broadcast Messages (resulting in position errors up to about ±200km) were sent out starting April 1, 2014, 21:00; Figure shows Errors in geocentric Earth-fixed y-coordinate of satellites of orbital plane 1.

Normal transmission resumed at different times for different satellites. Back to normal around 6h UT of April 2.

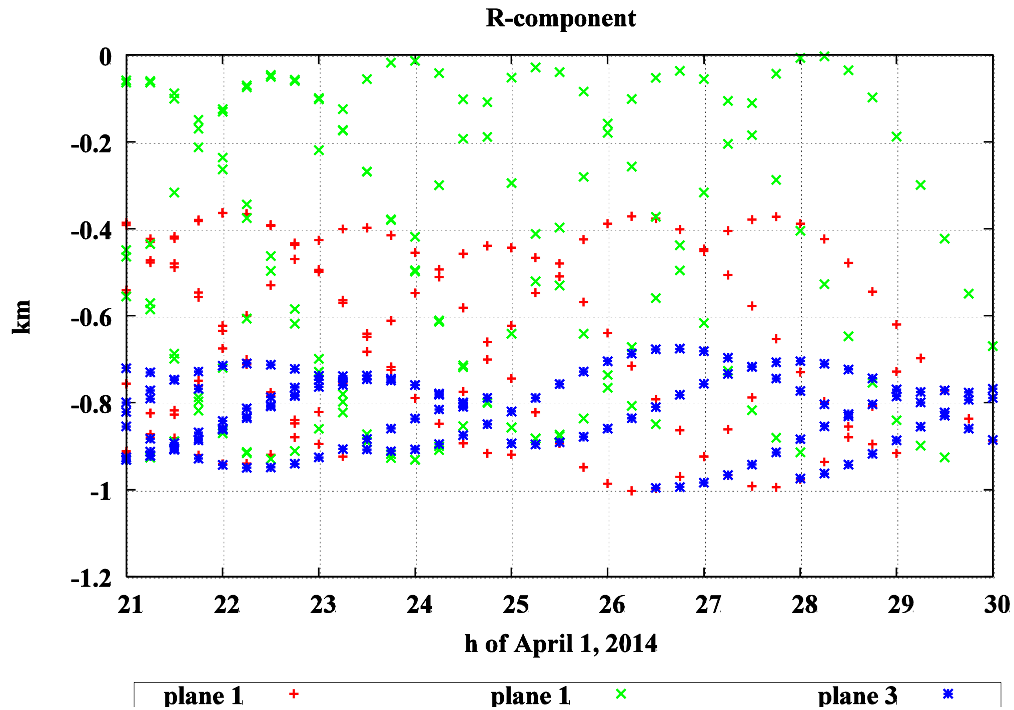
The GLONASS April 1st Incident



Bad Broadcast Messages (resulting in position errors up to about ±200km) were sent out starting April 1, 2014, 21:00; Figure shows errors in geocentric Earth-fixed z-coordinate of satellites of orbital plane 1.

Normal transmission resumed at different times for different satellites. Back to normal around 6h UT of April 2.

The GLONASS April 1st Incident in the IGS



Bad Broadcast Messages (resulting in position errors up to about ±200km) were sent out starting April 1, 2014, 21:00; Errors in radial coordinate R of satellites in orbital planes 1, 2, 3 are "only" of sub-km size.

Normal transmission resumed at different times for different satellites. Back to normal around 7h UT of April 2.

The GLONASS April 1st Incident

Satellite	RMS (F1_)	RMS(GL-1)	RMS(GL-2)
9, plane 2	0.03	0.31	0.30
10 , plane 2	0.01	0.43	0.32
11 , plane 2	0.03	0.31	0.47
12 , plane 2	0.01	0.36	0.29
13 , plane 2	0.03	0.36	0.35
14 , plane 2	0.01	0.43	0.34
15 , plane 2	0.02	0.58	0.40
16 , plane 2	0.01	0.34	0.31

The GLONASS April 1st Incident

Satellite	RMS (F1_)	RMS(GL-1)	RMS(GL-2)
17, plane 3	0.02	0.36	0.42
18, plane 3	0.01	0.60	0.36
19, plane 3	0.02	0.33	0.30
20, plane 3	0.02	0.39	0.29
21, plane 3	0.02	0.36	0.39
22, plane 3	0.01	0.34	0.80
23, plane 3	0.01	0.38	0.24
24, plane 3	0.01	0.35	0.40

The GLONASS April 1st Incident

Plane(s)	Rot x (“)	Rot y (“)	Rot z (“)	RMS (m)
1	-1762.83	5.40	2.06	56.1
2	-1763.44	5.20	2.18	54.8
3	-1763.47	5.81	2.04	81.4
all	-1763.25	5.28	2.09	70.7

Rotation of GLONASS GL-2 Broadcast Orbits w.r.t. CODE 1-d orbits F1_ , separately for each orbital plane. → no plane-specific systematics.

The GLONASS April 1st Incident in the IGS

The GLONASS Broadcast orbits GL-1 are consistent with the CODE precise orbits F1_ up to April 1st 2014, 20^{h}59^m UTC.

All GLONASS Broadcast Orbits of type GL-2 show a rotation w.r.t. the CODE precise orbits F1_ within the time interval April 1, 2014, 21^{h}00^m – April 2, 07^{h}00^m UTC.

The rotation takes place almost uniquely around the x-axis of the inertial equatorial coordinate system.

The GLONASS April 1st Incident in the IGS

The GLONASS April 1/2 event was almost a "non-event" in the IGS, because

- **Only about 1/3 of the GLONASS tracking data were missing in the time slot April 1, 21^h UT to April 2, 7^h UT.**
- **only combined GPS/GLONASS products (and no GLONASS-only products) are generated,**
- **no highly time-resolved products are generated,**
- **the conventional IGS analysis is performed calendar day by calendar day (UT) and**
  - **only 3 hours of GLONASS data were affected on April 1st,**
  - **only 7 hours of GLONASS data were affected on April 2nd.**

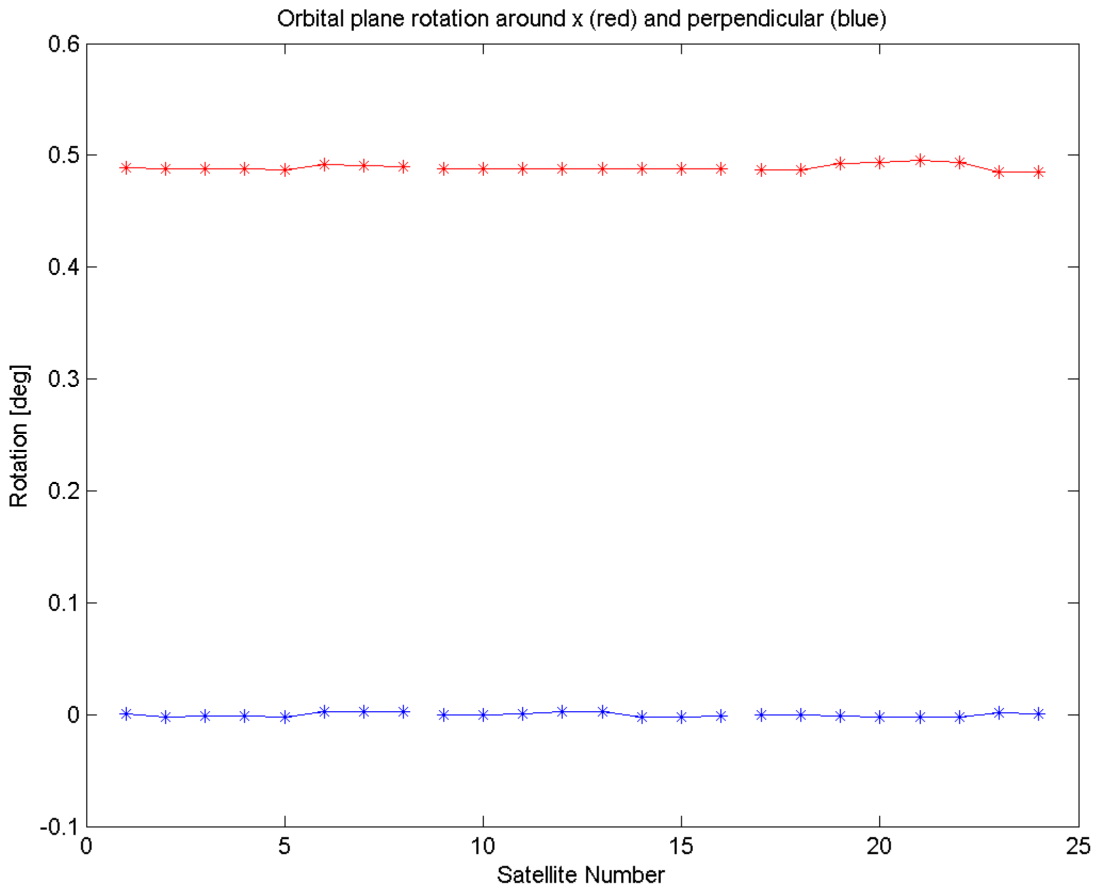
The GLONASS April 1st Incident

The result of slide 17 was independently checked:

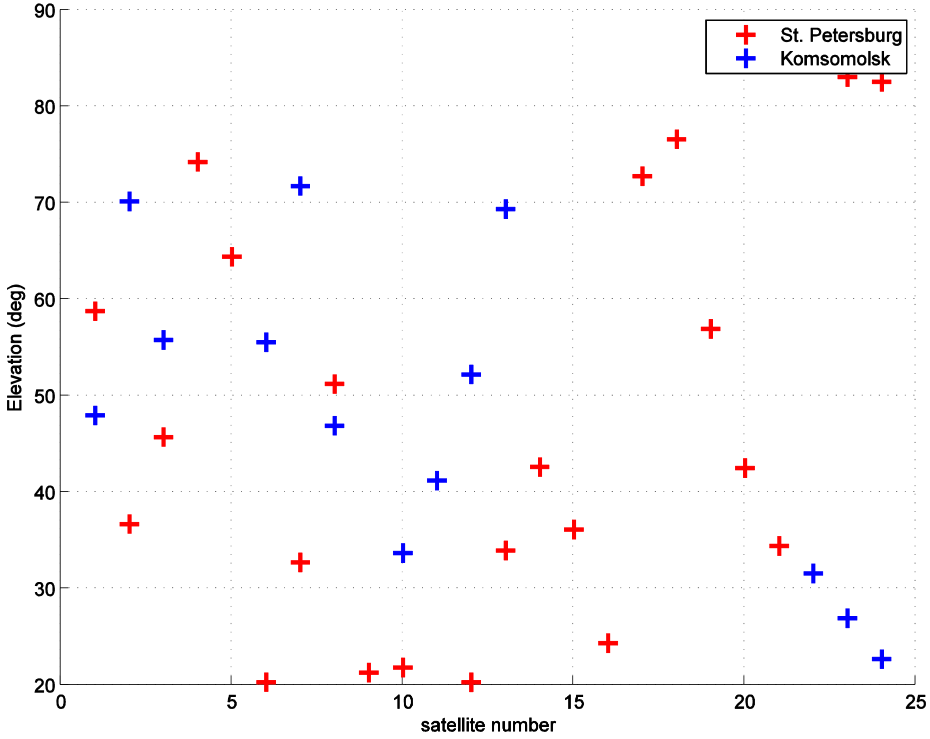
- **The differences of the orbit normal vectors of the GLONASS orbital planes, using correct & corrupted messages, respectively, were decomposed into a rotation about the x-axis and one perpendicular to it.**

- **The following figure shows that only the rotation about the x-axis differs significantly from zero – and corresponds to the values obtained with the standard method.**

The GLONASS April 1st Incident



The GLONASS April 1st Incident in the IGS



Epilogue: At the time of transition "back to normal" the satellites were visible (with an elevation of >20 deg) from at least one of the Command Tracking Sites on Russian Territory.