GNSS -a peak at the future

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Presentation Outline

GNSS: Global Navigation Satellite System

- GPS: overview, current signals, modernization
- GLONASS: history (rise-fall-rise), planned changes
- Galileo: planned constellation and signals
- Beidou-2 / Compass: announced information

- Impacts for mapping-grade positioning (code)
- Impacts for survey-grade positioning (carrier-phase)

Section 1: GPS
the *American* Father of GNSS

- History (ancient?)
- Current (legacy) signals
- Why GPS must change…and why it is hard to do
- Modernization phases

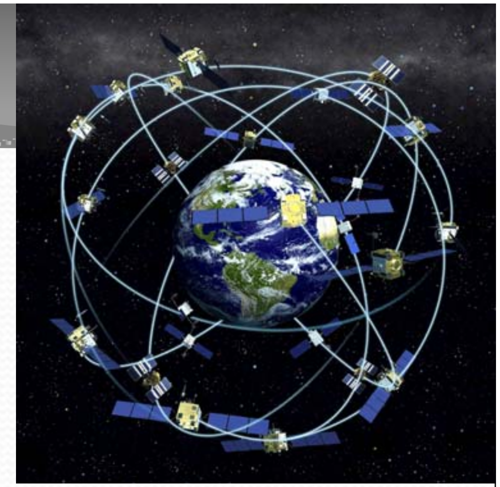
GPS - NAVSTAR

- GPS – **G**lobal **P**ositioning **S**ystem (*Civilian name*)
- NAVSTAR – **Nav**igation **S**atellite **T**iming **a**nd **R**anging (*Military name*)
- Conceived in the 1970s as a military tactical navigation tool, but has always been dual-use (*military & civilian*)
- First satellite launched Feb 1978…**over 31 years ago.. think about what was "high tech" back then!**

GPS – very early days

- 10 @ **Block I** GPS satellites (*test/prove phase*) launched 1978 – 1985…initially with open access to all frequencies and codes…but limited coverage
- **CA** code (coarse-acquisition *civilian*) broadcast on only the **L1** frequency
- **P** code (precise *military*) broadcast on both **L1** and **L2** frequencies…ionospheric errors can be removed
- Differential code techniques (DGPS) were developed and refined to improve accuracy & integrity
- Carrier-phase techniques were *invented*

GPS – 1990s



- **Block II** GPS Satellites (production)
- Constellation complete by 1993 (24 satellites) – 3D positioning possible anywhere in the world at any time
- **P** code encrypted…no direct tracking of L2 frequency (indirect “codeless” tracking possible, but more “fragile” than direct code tracking)
- **CA** code deliberately “wobbled” to induce civilian errors of ~100m horizontal (**SA**: Selective Availability)
- DGPS eliminates **SA**!
- Carrier-phase GPS replaces conventional methods for highest accuracy control establishment

GPS – waking up?

- 1996 Presidential Directive (Clinton) tells Military to take off **SA** (2000-2006)
- 1998 Vice President (Gore) introduces a GPS modernization plan
- May 2nd, 2000…the end of **SA** (*trying to take the wind out of Galileo's sails*?)…some call this the first step of modernizing GPS
- Autonomous GPS now has typical horizontal accuracies <10m 95% (*but with low integrity*)
- Recreational GPS for general navigation explodes and becomes the largest user segment (*by far*)

GPS – Modernization: L2C

- New civilian code on the L2 frequency (**L2C**)…different code structure to allow better tracking even though L2 transmit power levels are lower than L1
- Direct tracking of signals on 2 frequencies allows removal of ionospheric errors
- 8 existing Block II satellites sitting in warehouses were modified to include the **L2C** signal in order to make this enhancement available as quickly as possible
- First **Block IIR-M** satellite launched Dec 2005 (*currently 6 have been launched, and 2 more are planned to be launched in 2009*)

Satellites - Tracking Information

SV	Type	Elev. [Deg]	Azim. [Deg]	L1-C/No [dBHz]	L2-C/No [dBHz]	L1	L2	IODE	URA [m]	Type
30	GPS	10.20	32.09	42.8	19.6	CA	E	18	2	IIA
4	GPS	13.30	323.04	38.9	25.2	CA	E	4	2	IIA
13	GPS	15.48	264.56	39.9	19.6	CA	E	68	2	IIR
16	GPS	15.73	135.49	39.8	21.1	CA	E	57	2	IIR
11	GPS	17.16	215.53	43.0	27.6	CA	E	85	2	IIR
23	GPS	44.66	271.76	49.9	38.6	CA	E	57	2	IIR
31	GPS	48.27	59.26	50.2	40.6/47.8	CA	E/C	37	2	IIR-M
20	GPS	73.56	275.77	50.2	42.9	CA	E	68	2	IIR
32	GPS	75.06	145.40	50.8	42.5	CA	E	62	2	IIA

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GPS – Modernization: L5

- A new GPS frequency called **L5** will have new civilian codes and promise more robust tracking
- **L5** is in a "protected" frequency band (unlike **L2**), and it is greatly anticipated for critical navigation (and other) applications
- This signal will be included on a new version of satellites called **Block IIF**… 10 are being built, but there have been significant delays
- First **Block IIF** satellite *may* launch in 2009

Assembling a
Block IIF satellite…
this will give civilians direct access to 3 separate signals:

CA code on L1
L2C on L2
L5 code on L5

GPS – Modernization: L1C

- An entirely new generation is planned called **GPS III**, with these satellites called **Block III**
- This will include a number of phased enhancements, most importantly a new civilian code on the L1 frequency called **L1C**
- **L1C** has a different modulation type than all other GPS codes…the same modulation type as the planned Galileo codes…and this will make the manufacturing of combined GPS/Galileo receivers much simpler

GPS – Modernization: Ground Control

- The GPS Ground Control must modernize in-step with the new codes / signals
- This began a few years ago with the doubling of the number of ground control tracking locations, and the migration of the control software off mainframe (!) computers on to modern computer networks

GPS – Modernization Impacts

- **L2C** helps both mapping and survey-grade GPS by allowing direct tracking of a 2nd frequency
- **L5** will enhance critical navigation (e.g. aircraft), and it should also help reduce multipath for mapping-grade receivers, and will also improve wide-lane ambiguity resolution for survey-grade GPS (e.g. RTK)
- **L1C** will make GPS/Galileo combined receivers simple to make…and it may become the new “standard”
- ***All legacy signals continue, but 2020 has been set as a cutoff date for support of codeless tracking***

GPS – Modernization timing

- Each modernization phase takes time to build-out (full impact assumes ~24 satellites available)
- **L2C**: currently 6 IIR-M satellites are operating so only limited impact now, full impact by 2013-2015?
- **L5:** first launch may be 2009, full impact by 2015-2017?
- **L1C**: first launch may be 2013, full impact by 2019+

Note: these are my time estimates…not necessarily the "official" time estimates

GPS – Modernization timing

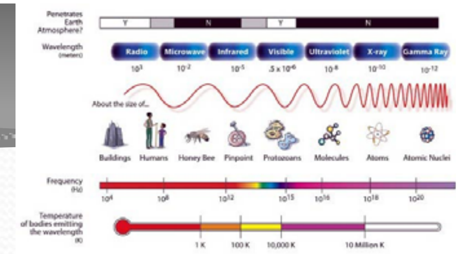
- Part of the "problem" for GPS is that the current satellites are lasting much longer than expected
- It is hard to justify launching new satellites (at a cost of $100 million each), when the current constellation is already over-populated (31 healthy satellites today)
- The oldest currently healthy GPS satellite was launched Dec 1990 (Brian Mulroney was PM!), and 9 are currently >15 years old (some in single-string failure mode)
- Design life: 10 years…the longer life has contributed to the delays of modernizing GPS

Section 2: GLONASS the *Russian* Uncle of GNSS?

- Technical comparison with GPS
- Development history
- Current re-building phase
- Modernization
- Using Glonass to augment GPS

GLONASS - Overview

- Glonass was developed during the cold war period as the USSR equivalent of GPS
- The basic concepts are similar, but there are technical differences (following slides describe some of the differences)
- The 24 satellite Glonass constellation was completed in 1995, but the collapse of the USSR, and many satellite failures, lead to a quick decay to only 6-8 healthy satellites by 2002
- In recent years Russia has made a commitment to re-build Glonass (planned completion: ~2010)
- Currently there are 20 healthy Glonass satellites, plus 2 more planned “triple” launches later this year



Glonass – codes and frequencies

- GPS satellites all transmit on the same frequency, but with different PRN codes (CDMA)
- Glonass satellites transmit using the same codes, but at slightly different frequencies (FDMA)
- Antenna & receiver designs for FDMA are more complex and can be harder to calibrate for the highest accuracy
- Combined GPS / Glonass receivers are available for survey/mapping, but are not likely for mass-markets
- There are indications that Glonass may try CDMA in the future (same as GPS, Galileo, Compass)

Glonass – codes and frequencies

- Glonass satellites transmit civilian codes at both L1 and L2 frequencies…this has always allowed civilian receivers to directly track signals in 2 frequency bands (*this is just starting for GPS*)
- These codes have never been deliberately degraded (*unlike SA on GPS*)
- *Who would have thought???*

Glonass – orbits and Ground Control

- Glonass orbits are inclined steeper than GPS (65^{o} compared to 55^{o})…this gives slightly better coverage at high latitudes
- Glonass satellites repeat every 8 days…GPS repeats every day (actually 23h56m)
- The Glonass Ground Control is limited to tracking stations only in former USSR territory (*not global like GPS*)…this limits the ephemeris accuracy.

SV	Type	Elev. [Deg]	Azim. [Deg]	L1-C/No [dBHz]	L2-C/No [dBHz]	L1	L2	IODE	URA [m]	Type
7	GLONASS	20.41	132.31	45.0/43.8	37.7	CA/P	P	19	N/A	M
8	GLONASS	73.81	111.90	52.9/49.8	48.8	CA/P	P	19	N/A	M
9	GLONASS	26.24	36.20	49.6/47.2	-	CA/P	-	19	N/A	M
10	GLONASS	77.67	77.90	51.9/49.1	43.2	CA/P	P	19	N/A	M
11	GLONASS	38.89	200.98	51.2/48.5	44.4	CA/P	P	19	N/A	M
17	GLONASS	11.19	327.11	42.6/39.7	37.3	CA/P	P	19	N/A	M
13	GPS	17.65	266.28	42.2	22.5	CA	E	68	2	IIR
31	GPS	45.96	57.49	50.8	40.7/47.4	CA	E/C	37	2	IIR-M
16	GPS	18.02	133.90	40.8	22.8	CA	E	57	2	IIR
32	GPS	72.16	145.92	50.3	41.7	CA	E	62	2	IIA
4	GPS	14.88	321.26	41.4	24.1	CA	E	4	2	IIA
11	GPS	15.02	214.13	42.3	24.8	CA	E	85	2	IIR
20	GPS	75.30	267.14	50.5	43.5	CA	E	68	2	IIR
23	GPS	47.04	273.86	51.8	39.6	CA	E	57	2	IIR

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SV	Type	Elev. [Deg]	Azim. [Deg]	L1-C/No [dBHz]	L2-C/No [dBHz]	L1	L2	IODE	URA [m]	Type
6	GLONASS	27.11	45.45	45.7/43.5	38.1	CA/P	P	89	N/A	M
7	GLONASS	84.02	317.68	50.3/48.5	45.7	CA/P	P	89	N/A	M
21	GLONASS	24.56	157.56	49.0/46.4	41.4	CA/P	P	89	N/A	M
22	GLONASS	75.69	202.32	52.9/50.4	48.3	CA/P	P	89	N/A	M
8	GLONASS	33.28	231.47	49.8/47.0	43.7	CA/P	P	89	N/A	M
23	GLONASS	38.57	320.94	48.5/46.0	37.0	CA/P	P	89	N/A	M
15	GLONASS	12.16	19.42	43.2/40.8	39.2	CA/P	P	89	N/A	M
22	GPS	48.06	228.81	49.7	38.6	CA	E	57	2.8	IIR
29	GPS	10.53	154.64	41.8	27.5/40.8	CA	E/C	75	2	IIR-M
16	GPS	18.25	247.26	42.8	26.7	CA	E	59	2	IIR
24	GPS	20.66	98.71	44.2	28.3	CA	E	86	2.8	IIA
15	GPS	33.71	58.33	48.2	36.7/45.3	CA	E/C	65	2	IIR-M
6	GPS	48.62	290.84	47.3	38.5	CA	E	28	2	IIA
3	GPS	37.03	301.18	46.3	35.9	CA	E	63	2	IIA
21	GPS	66.23	93.03	50.2	41.9	CA	E	104	2	IIR
26	GPS	24.55	44.15	43.8	30.9	CA	E	59	2	IIA
18	GPS	81.44	199.86	47.4	41.7	CA	E	35	2	IIR

Combined GPS + Glonass…example #3 (RTK Rover)

PC-CDU to GB500 ID:8RT1TVB083K (rover)

File   Configuration   Tools   Plots   Help

GPS Satellites (11)

#	EL	AZ	CA	P1	P2	TC	SS
03	14+	312	44	25	25	25	55+
06	27+	308	44	31	32	53	55+
10	11–	48	42	22	22	53	55+
15	36+	92	48	36	36	53	55+
16	34–	274	47	34	34	53	55+
18	52+	206	52	41	41	53	55+
21	83+	326	51	44	45	53	55+
22	21+	218	46	29	30	39	55+
24	44–	82	50	37	37	53	55+
26	33+	76	47	34	35	53	55+
29	38–	148	47	38	38	53	55+

Geo   XYZ   Target

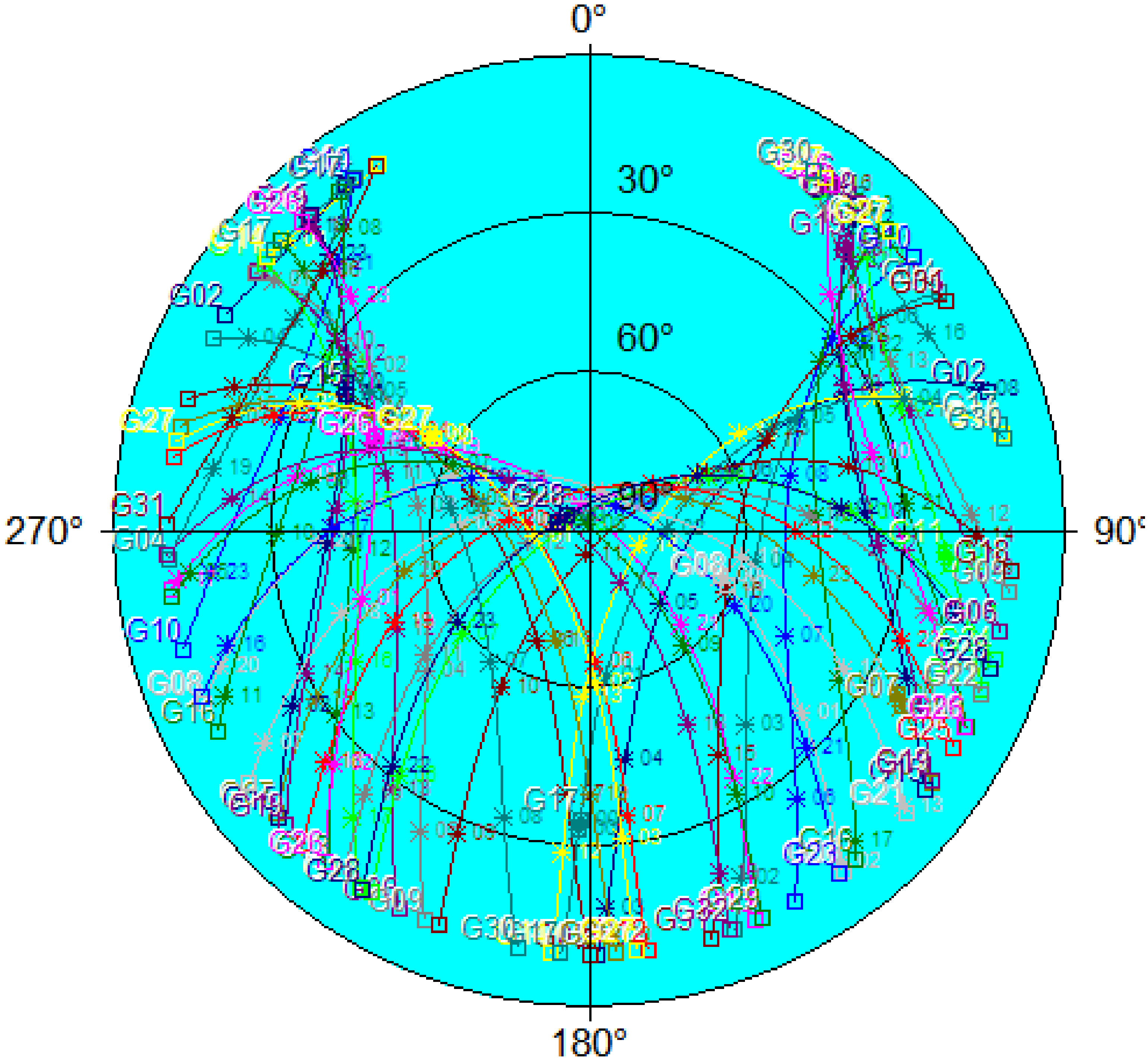
Lat: 49° 09' 54.9790" N
Lon: 123° 57' 09.7265" W
ETT: -0.008 m
NTT: -0.001 m
DTT: 0.008 m
CTT: 260° 17' 10.79"
PDOP: 1.4724
(RTK fixed)
LQ: 100% (001,7604,0000)

Receiver time: 18:17:04
Receiver date: 05/03/2009
Clock offset: -0.4865 ppm
Osc offset: -0.4865 ppm

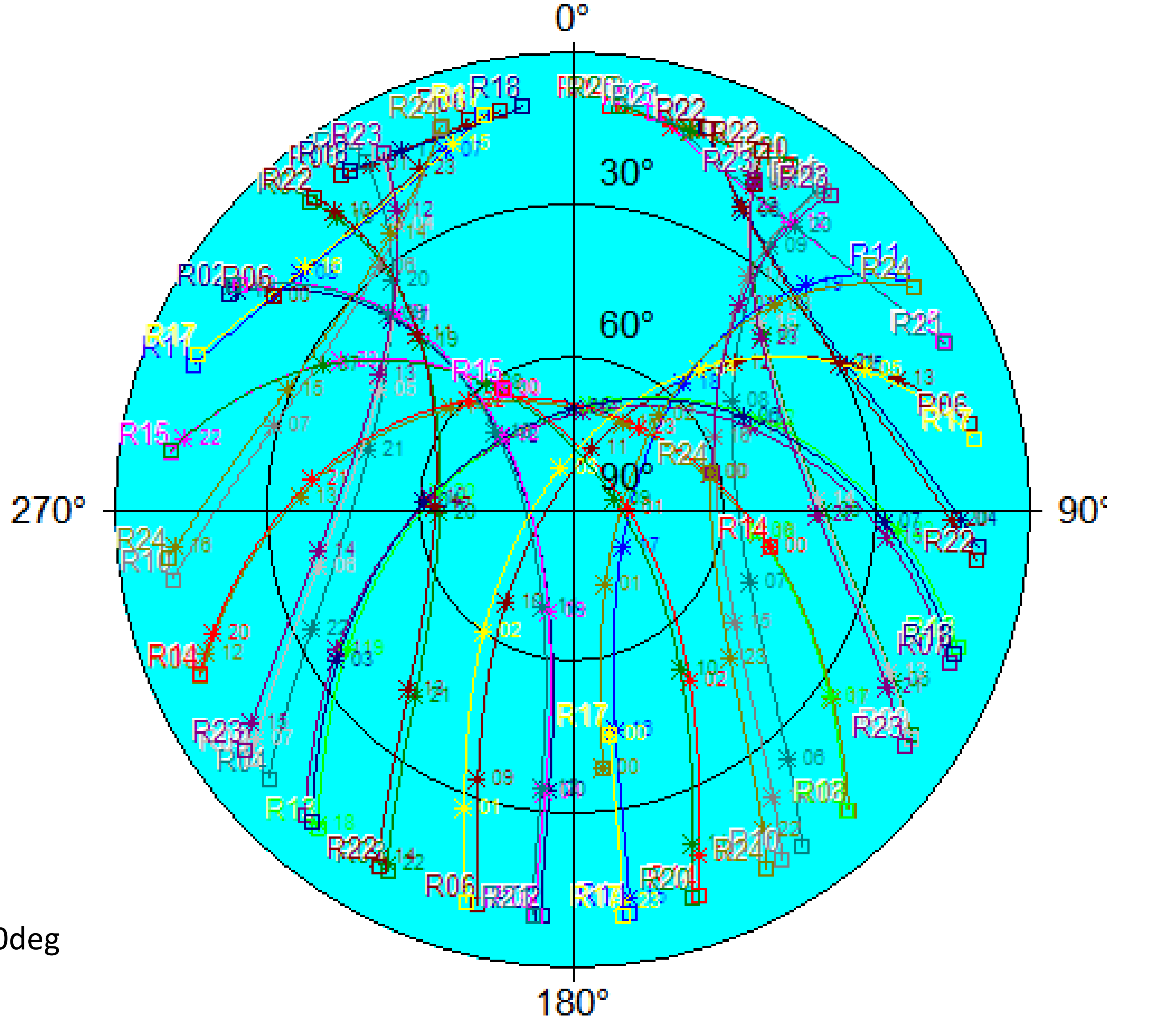
GLONASS Satellites (9)

Sn	Fn	EL	AZ	CA	P1	P2	TC	SS
21	-1	58–	140	52	51	48	53	55+
06	01	59–	44	48	48	44	53	55+
22	-3	63+	320	51	51	48	53	55+
20	02	7–	140	32	30	30	1	30–
07	05	55+	212	52	52	43	53	55+
13	-2	4–	312	39	38	31	53	30–
14	04	10+	358	41	41	35	46	55+
23	03	9+	320	38	38	29	11	30–
08	06	5+	214	40	39	35	:57	30–

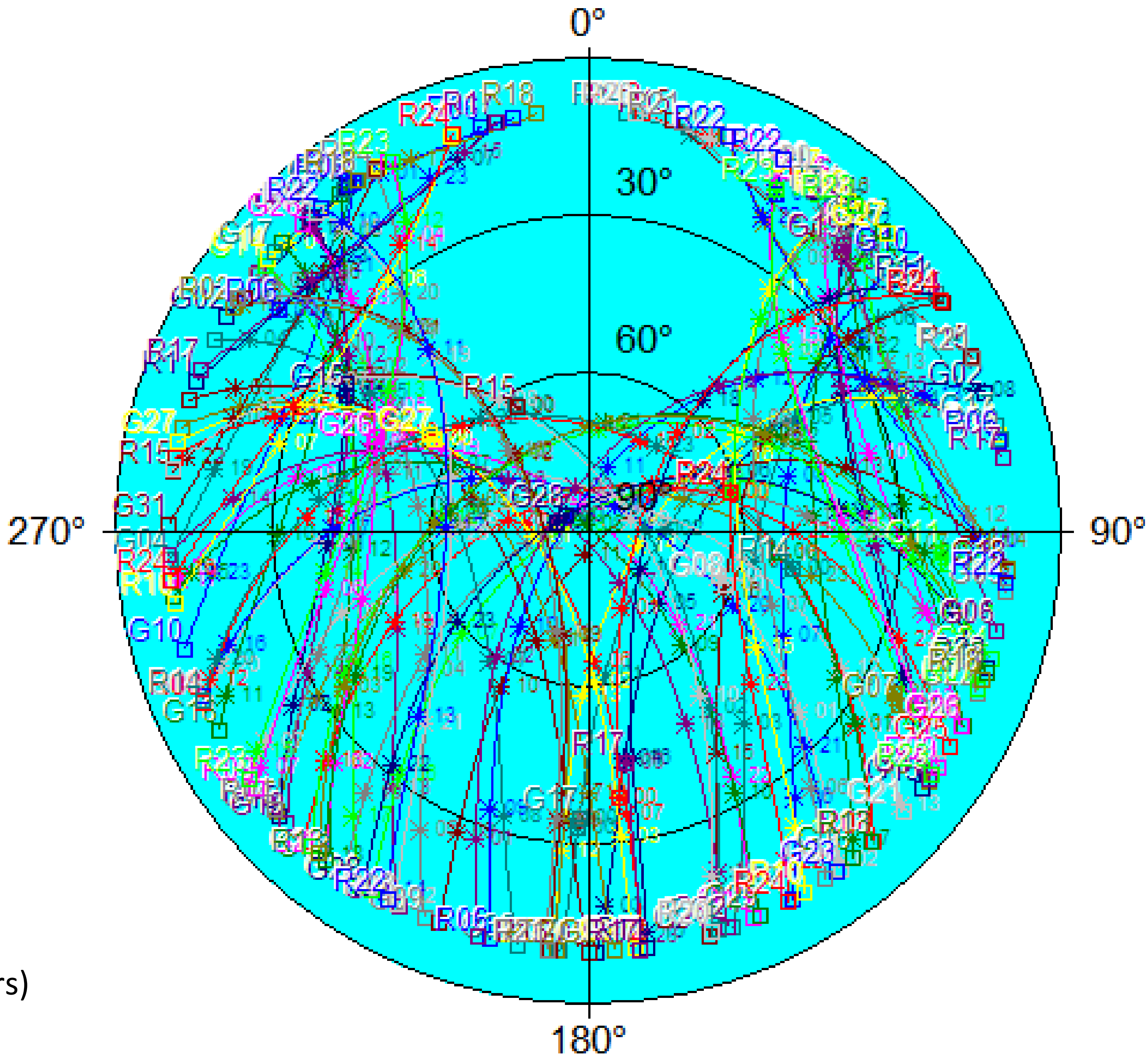
RTK solution using 11 GPS and 5 Glonass satellites (only satellites marked "55+" are being used in the solution). The computed position is 8mm from known coordinates. Notice Glonass #14: 10 degrees elevation in the North (Az 358)…GPS satellites are never in this part of the sky for a user with Latitude 49. *This is for illustration only…it is not generally recommended to use satellites at these low elevation angles.*



GPS Only (10deg mask, 24 hrs)

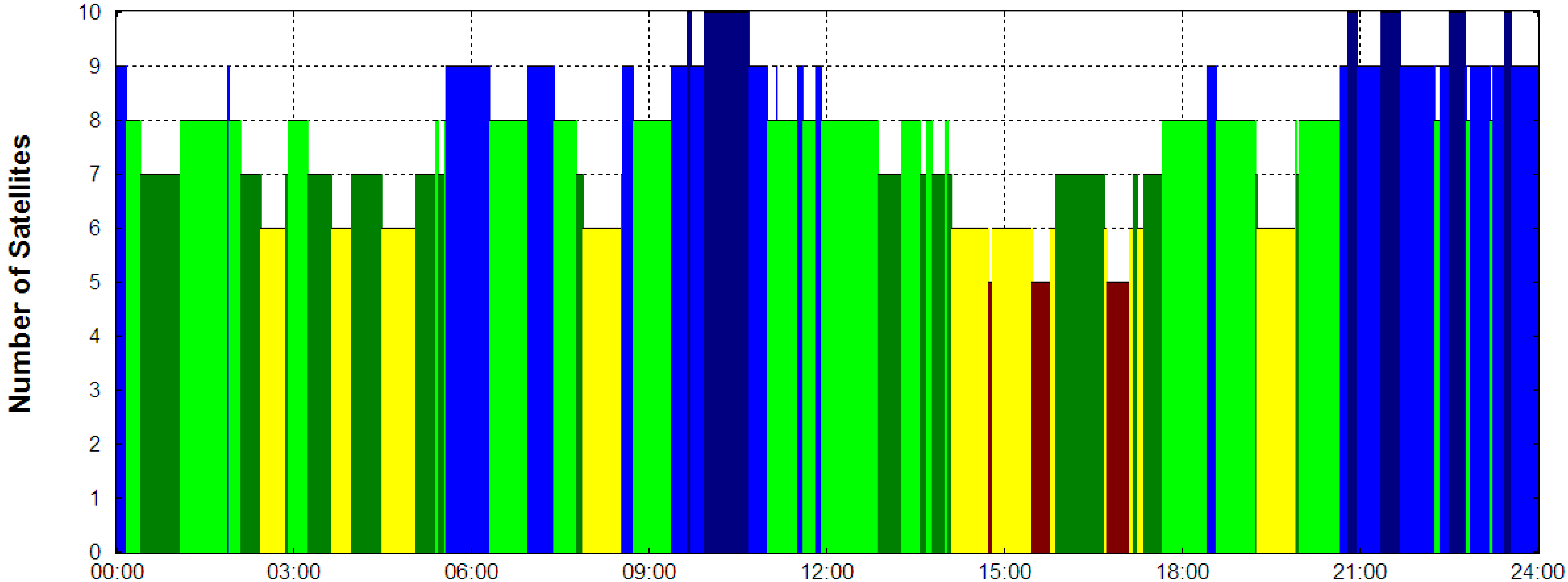


Glonass only (10deg mask, 24 hrs)



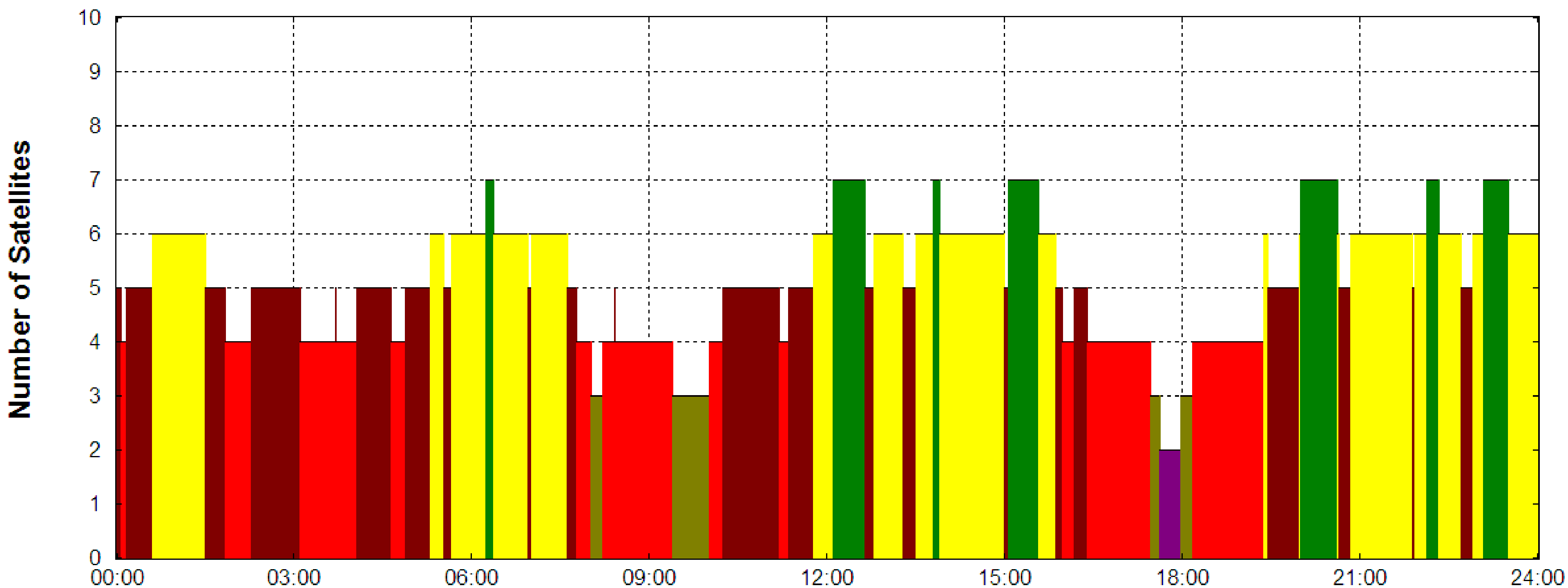
GPS plus Glonass
(10deg mask, 24hrs)

Visibility



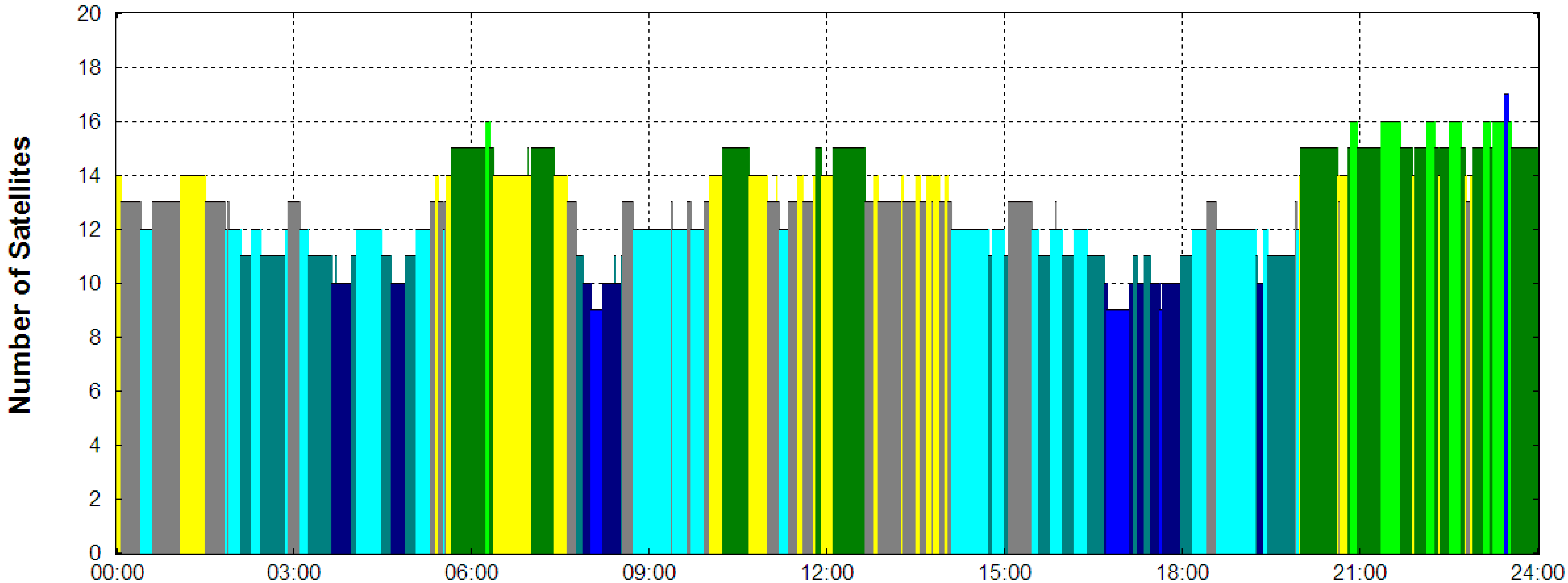
GPS only (15deg mask, 5 – 10 satellites visible)

Visibility



Glonass only (15deg mask, 2 – 7 satellites visible. Notice that the weakest time for Glonass is after the weakest time for GPS…not every day will be this lucky)

Visibility



GPS plus Glonass (15deg mask, 9 – 17 satellites visible)

Glonass - summary

- Currently in a re-building stage…constellation complete in 1-2 years
- Initially, Glonass was not taken seriously, but this has changed in the last few years (particularly RTK users)
- Even without a full constellation, Glonass is ***very*** useful as an augmentation to GPS
- Much of the existing infrastructure is GPS-only, and therefore users may have to run their own “base” stations
- To stay “relevant” and expand into mass markets, Glonass may have to change from FDMA to CDMA (big shift)

Section 3: Galileo
– *Europe's* new kid on the block?

Why build Galileo?

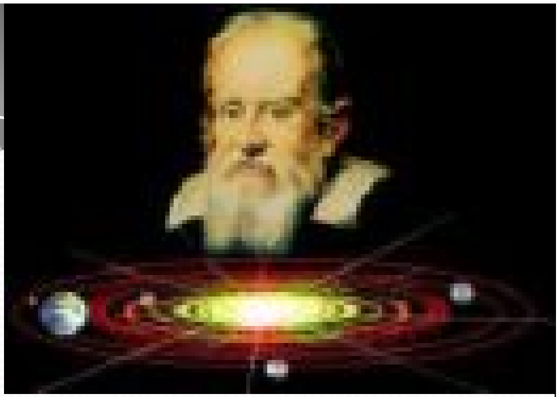
Slow first steps…PPP falls apart…re built as a Public Utility

Design highlights

Two test satellites up now

Planned schedule and impacts

Galileo - overview

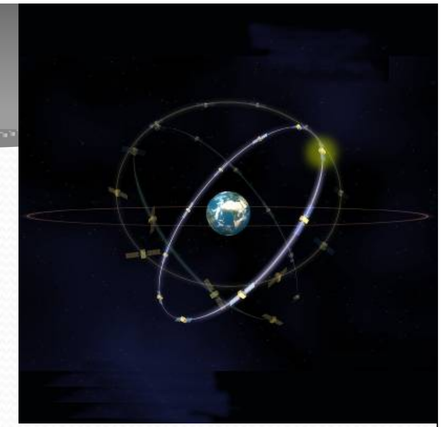


- Europeans have long talked about having their own GNSS…driven by reasons including sovereignty / civilian control / high-tech jobs *(and a general dislike of most things American)*
- EGNOS is the European equivalent of WAAS, and serves as a local improvement to GPS…and it has been called the first step towards a European GNSS
- After much discussion, a PPP development model was proposed, and years were invested in this approach before the wheels came off in 2007
- The development model is now based on Galileo being built as a public utility (EU and ESA), with participation of Israel, Ukraine, India, Morocco, Saudi Arabia, S Korea (*and China?)*

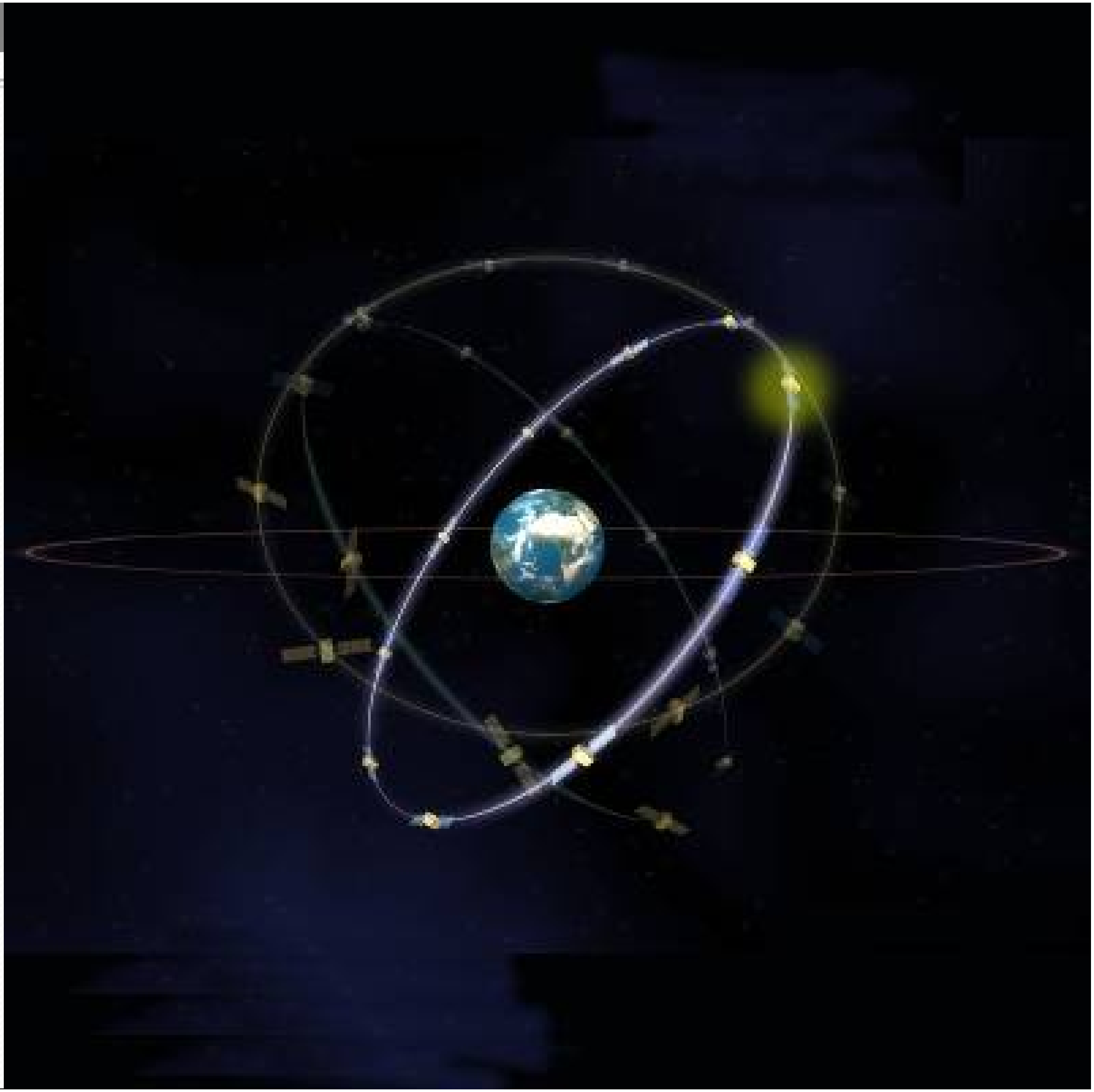
Galileo - overview

- There is a ***huge*** advantage for a GNSS being planned and built now: *thirty years of experience with GPS and Glonass!*
- This could lead to a new GNSS leapfrogging the performance of existing systems (accuracy, availability, integrity)
- The “inertia” of the existing GNSS means it is hard for them to adapt quickly, and they could be left behind

Galileo - design



- 30 satellites in 3 orbital planes (slightly higher inclination than GPS, but not as much as Glonass)
- *Hydrogen Maser* clocks (better stability and therefore better range accuracy than current GPS clocks)
- CDMA (same as GPS, all satellites broadcast at the same frequencies, but with different codes), with 4 *services*:
- **OS** (Open Service), free, 2 frequencies, accuracy aprox same as GPS
- **CS** (Commercial Service), encrypted, fees, 3 frequencies, accuracy <1m
- **PRS** (Public Regulated Service) and **SOL** (Safety Of Live), encrypted, same accuracy as OS, but with very high integrity and resistance to jamming



Galileo – 3 orbital planes @ 56deg inclination

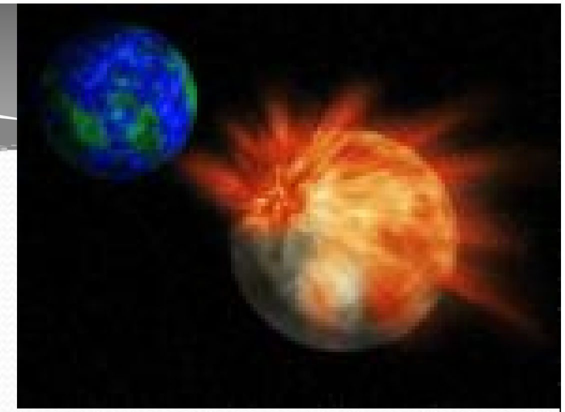
Galileo - interoperability

- USA was initially hostile to the idea of Galileo, particularly with it being under completely civilian control
- This tension has since relaxed, and in 2004 there was an interoperability agreement signed between EU and USA
- This agreement clarifies the technical details of frequencies and code modulation (e.g. the new GPS civilian code L1C will be modulated the same way as Galileo signals)
- Note that the “defining” document of how Galileo works (ICD: Interface Control Document) is still in draft form…*it is not correct for manufacturers to claim that equipment will track production Galileo satellites.*

Galileo - timing

- Two test Galileo satellites are currently orbiting, and a 3rd is being readied for launch
- Next, 4 “production” satellites will be launched into 2 orbits for proof-of-concept (2011?)
- Finally, the remaining 26 production satellites will be launched (2012 – 2016?)
- Compare these dates with GPS modernization (L2C, L5, and L1C)…*the race is on!*

Galileo - impact



- Galileo will significantly impact survey/mapping GNSS users by increasing *availability* (30 more satellites), *accuracy* (better clocks, and more robust signals), and *integrity* (redundancies / signals)
- This impact will ramp-up as Galileo satellites are launched (starting as an augmentation to GPS, and becoming a fully independent GNSS upon completion)
- Joint use of GPS - Galileo will likely be easier than GPS – Glonass (time referencing, datums, CDMA/FDMA, etc), and this will lead to mass-market combined receivers

Section 4 Compass / Beidou-2 - the *Chineese* unknown?

Beidu-1 regional coverage

Surprise announcement 2007: Global System

What we know…(*not a lot*)

Beidou-1 regional system

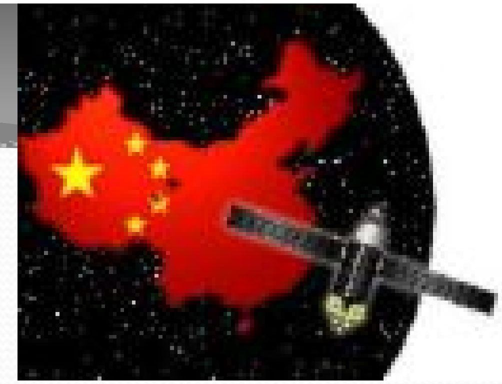
- 4 geo-stationary Beidou-1 satellites were launched by China 2000-2007, giving some regional coverage (not a GNSS)
- Very different operating principles:

1. A signal is transmitted skyward by a remote terminal
2. Each of the geostationary satellites receive the signal
3. Each satellite sends the accurate time of when each received the signal to a ground station
4. The ground station calculates the longitude and latitude of the remote terminal, and determines the altitude from a relief map
5. The ground station sends the remote terminal's 3D position to the satellites
6. The satellites broadcast the calculated position to the remote terminal

Beidou-2 / Compass

- Surprise announcement late 2006: China will build a GNSS
- Test satellite launched April 2007 (within 3 months independent US and European agencies had decoded and published the signals!)
- Design: 30 satellites in inclined orbits (very similar to GPS and Galileo), plus 5 geo-stationary satellites
- Frequencies overlapping closely with Galileo, and CDMA signals very similar to Galileo and modernized GPS …potential problems!
- Plans for 2 services: *open* and *restricted*

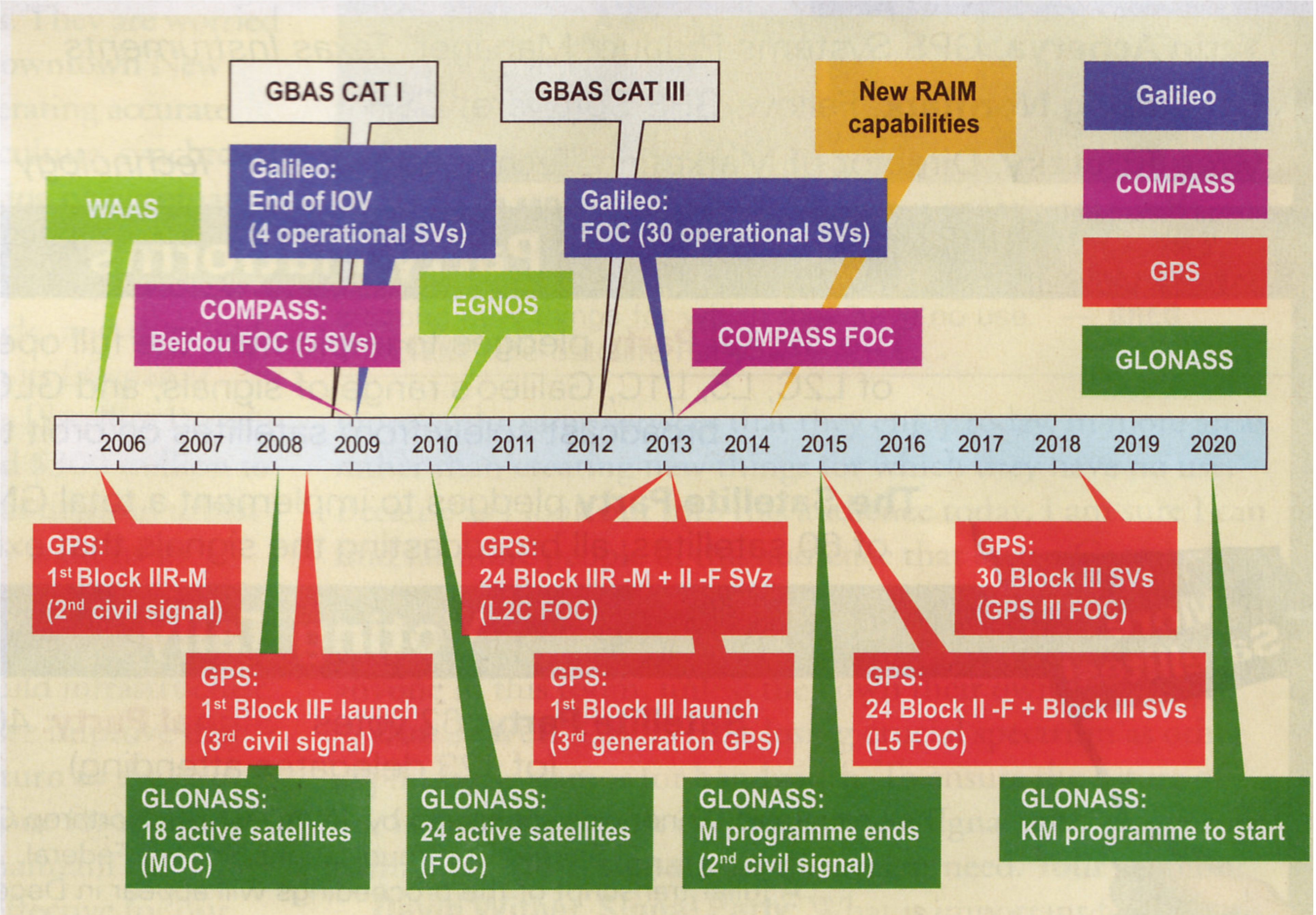
Beidou-2 / Compass - Impact



- Announced date for completion: 2015?
- Some manufacturers already claim they can track Compass, but at this very early development stage *very* little is really known (no ICD released yet)
- For users…there is a diminishing-return as more and more satellites and signals become available

GNSS - Summary

- Political & Industrial competition is driving GNSS developments…and the user will benefit!
- Very significant changes are coming in the next decade
- 100 (or more) navigation satellites could be available…with a multitude of different signals being broadcast from each satellite
- Think about the impact and timing of these changes when considering equipment purchases!
- Next slide is from GPS World magazine (11/2008)



GNSS DEVELOPMENTS AND AVIATION

From GPS World, 11/08