UNIVERSITÉ DE TECHNOLOGIE DE BELFORT-MONTBÉLIARD

Global Navigation Satellite Systems

LO53 Part II

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1. Global Navigation Satellite System
2. Global Positioning System
   - Basics
   - GPS Augmentation Systems
3. Other GNSS
   - GLONASS
   - Galileo

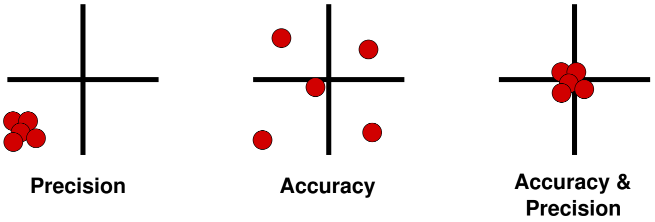
1. Global Navigation Satellite System
2. Global Positioning System
3. Other GNSS

Definition

- Global Navigation Satellite System
- Defined by :
  - Accuracy/Precision
  - Longitude/Latitude
  - Constellation
  - History

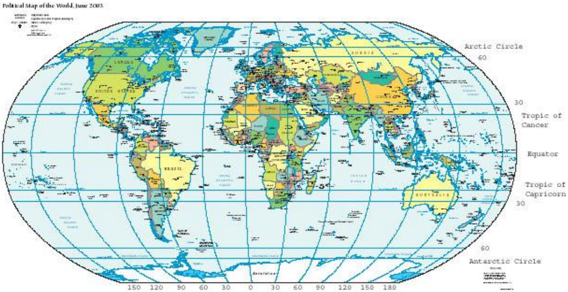
Accuracy and precision

- Precision : quality of points between themselves,
- Accuracy : quality compared to the true location.



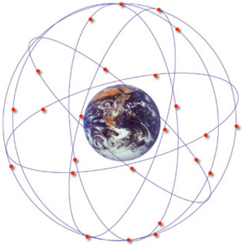
Definition : Latitude/Longitude

- Latitude : from 0 to 90, oriented N/S from the equator
- Longitude : Greenwich Meridian, from -180 to +180



Definition : Constellation

- Orbiting satellites



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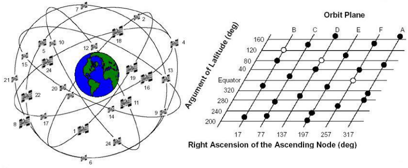
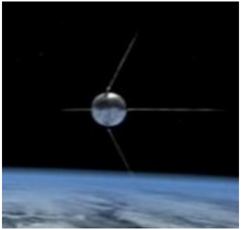


(b)

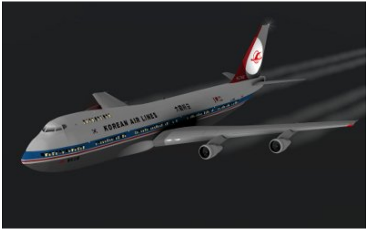
GNSS history

- 1957 : Spoutnik
- 1960-70 : System Transit (Doppler, accuracy $\simeq$1km, 1100 km,106min)
- 1978 : first GPS satellite
- 1982 : first Glonass satellite



GNSS history

- 1983 : KAL flight 007 shot down by soviet army
- Consequence : U.S.A Pdt. Ronald Reagan announced GPS availability to civilian applications.



GNSS history

- 1994 : GPS constellation complete
- 1995 : Glonass constellation complete
- 2000 : Selective Availability discontinued
- 2004 : first Galileo satellite

1. Global Navigation Satellite System
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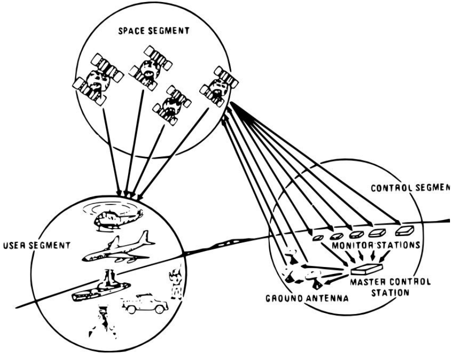
   - GPS Augmentation Systems
3. Other GNSS

Segments (GPS)



Space Segment : constellation (1)

- Nominal GPS constellation
  - Semi-major axis : a=26560km
  - Altitude 20200km
  - Excentricity < 0.01 (almost circular orbit)
  - Period : $\simeq$12h ($v = 4000$ m.s^{-1})
  - Six orbital plans (A-F) every 60˚
  - 4 satellites on each plan, unequally distributed (failure tolerance)
  - Requires 24 satellites

Space Segment (2)

- Currently 31 satellites (old ones)
  - Redundant measurements
  - Improves
    - Reliability
    - availability
- Almost everywhere on Earth : at least 6 satellites within line of sight

Control Segment (1)

- Monitor Stations
  - Receive orbital data
- Ground antennas (uplink stations)
  - Transmit updates to satellites
- Master Station
  - Data processing
  - Time and orbits updates

Control Segment (2)

- Schriever AF base
  - 2nd Space Operations Squadron (2SOPS)
  - Receives tracking data from monitor stations
  - Sends navigational updates to satellites through ground antennas
    - Synchronizes atomic clocks a few ns from each other
    - Adjusts ephemeris of satellites internal orbital model
    - Based on Kalman filter on various inputs

Satellite trajectory change

- Not precised by GPS standards
- Mark satellite as “unhealthy”
  - Users won’t use it
- Move it
- Orbit tracked
- Ephemeris updated and uploaded
- Satellite marked “healthy” again

User Segment (1)

- Who ? Army – fleet management – agriculture – navigation – emergency services – customers = you
- Receivers with various qualities
- Shared functions :
  - Satellites (in sight) identification
  - Computation of distance between user and satellites, then trilatération
- Additional functions :
  - Ease and/or improve positioning
  - Add services (route, integration to communication systems, etc.)

User Segment (2)

- GPS receiver composed of
  - An antenna
    - tuned to the satellite frequencies
  - Receiver processors
  - Highly stable clock (crystal oscillator)
- Defined by number of channels
  - Number of satellites simultaneously tracked
  - At the beginning 4 or 5 channels
  - Nowadays, from 12 to 20

User Segment (3)

- Transmits data to a PC by
  - NMEA protocol
    - NMEA 0183
    - NMEA 2000
    - Allow open source tools (gpsd)
  - Proprietary protocols
    - SiRF
    - MTK
- Can transmit througs serial, USB, bluetooth, etc.

Frequencies

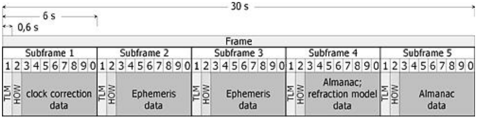
- L1
  - 1575.42 MHz
  - C/A and encrypted P(Y) code
- L2
  - 1227.60 MHz
  - P(Y) code
- L3, L4, L5 for further use

GPS signals

- Each satellite broadcasts a navigation message
    - 50 bps
    - 25 frames (30 seconds each)
    - 12.5 min required to receive the whole data
- Each frame
    - 5 subframes (300 bits)
- Each subframe
    - 10 words (30 bits)

Frame structure

- TLM (Telemetry Word)
  - Marks beginning of subframe
  - Sync. with navigation message
- HOW (Hand Over Word)
  - Timing information
  - Identify subframe
  - Time next subframe was sent



Subframe 1 to 3

- Subframe 1 : clock correction data
  - Status and accuracy of current satellite
    - Satellite clock and relation to GPS time
- Subframes 2 & 3 : ephemeris (current sat.)
  - Current satellite precise orbit
  - Updated every 2 hours
  - Valid for 4 hours
  - The older the ephemeris, the longer the warm start

Subframes 4 & 5 : almanac data

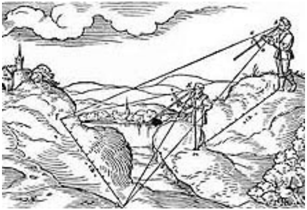
- Coarse data
  - Orbits
  - Status
  - For EACH satellite
    - Each frame is 1/25 almanac data
- When no almanac
  - Cold start
  - Up to 12.5 min to get all data from nothing
- Purposes of the almanac
  - Acquisition of satellites
  - Relates GPS time to UTC time
  - Allow single-frequency receiver to correct ionospheric error
    - Global ionospheric model

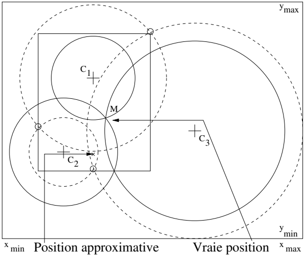
Decoding C/A signals

- C/A (Coarse Acquisition) gold code
  - 1023 bits
  - 1025 different codes
- Problems
  - Doppler shift
  - Requires the almanac

How it works : basics (1)

- Triangulation
  - Angle-based method
  - Easy to use and measure
- Trilateration
  - Distance-based method
  - Easy to automate
  - Hard to measure (accuracy)





How it works : basics (2)

- Distance determination :

$$d = c \cdot \tau$$

with c being light speed

$$c \simeq 300000000 m.s^{-1}$$

- Works with synchronisation
- $1 \mu s$ error gives a 300 meters error

How it works : time

- Satellite : atomic clock
  - Very precise, low deviation, high cost
  - Problem : relativity
- Receiver : quartz clock
  - Low cost , high deviation (relative to satellites atomic clocks)
- Deviation measurement is critical

How it works : formula

- Formula to compute (x_u, y_u, z_u) coordinates according to 4 satellites

$$\begin{cases} \rho_1 = \sqrt{(x_{s_1} - x_u)^2 + (y_{s_1} - y_u)^2 + (z_{s_1} - z_u)^2} + c \cdot \delta t_u \\ \rho_2 = \sqrt{(x_{s_2} - x_u)^2 + (y_{s_2} - y_u)^2 + (z_{s_2} - z_u)^2} + c \cdot \delta t_u \\ \rho_3 = \sqrt{(x_{s_3} - x_u)^2 + (y_{s_3} - y_u)^2 + (z_{s_3} - z_u)^2} + c \cdot \delta t_u \\ \rho_4 = \sqrt{(x_{s_4} - x_u)^2 + (y_{s_4} - y_u)^2 + (z_{s_4} - z_u)^2} + c \cdot \delta t_u \end{cases}$$

Pseudo ranging

$$\rho = \sqrt{(x_s - x_u)^2 + (y_s - y_u)^2 + (z_s - z_u)^2} + c \cdot t_u + c \cdot t_a + E_j + \eta$$

- t_a : atmospheric error, related to propagation through ionosphere and troposphere $(t_{iono} + t_{tropo})$
- E_j ephemeris error
- η are other errors

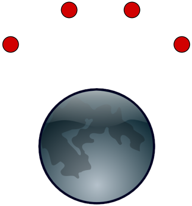
How it works : notes

- A receiver requires at least 4 satellites to determine its location
- Satellites must be in sight of the receiver
- The more satellites are on sight, the better the location determination

DOP

- DOP = Dilution of Precision
- GDOP = Global Dilution of Precision
- VDOP = Vertical Dilution of Precision
- HDOP = Horizontal Dilution of Precision

(c)



(d)

DOP computation

- From statistical data
  - Errors
  - Variances : σ_E^2, σ_N^2, σ_U^2, σ_d^2

$$GDOP = \frac{\sqrt{\sigma_E^2+\sigma_N^2+\sigma_U^2+\sigma_d^2}}{\sigma}$$
$$PDOP = \frac{\sqrt{\sigma_E^2+\sigma_N^2+\sigma_U^2}}{\sigma}$$
$$HDOP = \frac{\sqrt{\sigma_E^2+\sigma_N^2}}{\sigma}$$
$$VDOP = \frac{\sigma_U}{\sigma}$$
$$TDOP = \frac{\sigma_d}{\sigma}$$

GDOP

- Sat. Position (when measuring) greatly interferes on the location estimation.
- Instant quality of positioning bound to satellites locations is given by GDOP
- Good GDOP : close to 1

Errors

Segment	Error source	PPS	SPS	SA
Space	Clock stability	3	3	3
	Satellites	1	1	1
	Selective Availability			32.2
	Other	0.5	0.5	0.5
Control	Ephemeris	4.2	4.2	4.2
	Other	0.9	0.9	0.9
User	Ionospheric	2.3	5	5
	Tropospheric	2	1.5	1.5
	Receiver noise	1.5	1.5	1.5
	Multipath	1.2	2.5	2.5
	Other	0.5	0.5	0.5
Total		6.6	8	33.3

Accuracy

- Real-time :
  - GIS constraints
  - Generally 15 meters error
  - Hard to estimate the error
- DGPS
  - Longer measurements
  - Error of about 10 cm

Interferences

- Jamming
- Radio waves
- Canyon (cities)
- Sun
- Weather
- Time of the day
- Multipath

Limits

- Good relative position
- Requires a free-sight to the sky
- Depends on only one provider
- No integrity
- Easy to jam (civilian applications)

Conclusion

- Advantages
  - Fully operational
  - Good accuracy/precision
  - Existing augmentation systems (EGNOS, WAAS)
- Drawbacks
  - Under U.S.A military control
  - Only one civilian mode

NMEA Protocol

- National Marine Electronics Association
- Initially, protocol designed for sea navigation
- Extended to GPS use, well documented, about 30 frames defined

Example

```
$GPGGA,064036.289,4836.5375,N,00740.9373,E,1,04,3.2,200.2,M,,,,0000*0E
```

- 064036.289 : frame time 06h40m36.289s
- 4836.5375,N : latitude 48˚ 36.5375' North
- 00740.9373,E : longitude 7˚ 40.9373' East
- 1 : positioning type (1 stands for GPS)
- 04 : number of satellites used to compute coordinates
- 3.2 : Horizontal precision (HDOP : Horizontal dilution of précision)
- 200.2,M : Altitude 200.2 , meters
- ,,,,,0000 : other data might be displayed in these fields
- *0E : Checksum, simple XOR on the frame string

Main GPS frames (1)

- GPALM : almanac status (for a specified satellite)
- GPGBS : satellite fault detection
  - Expected errors for a GPGGA/GNS frame
- GPGGA : GPS fix data
  - Latitude/Longitude specified with minutes (convert to degree)
- GPGST : pseudo-range noise (associated to GGA)
- GPGSA : PDOP, VDOP, HDOP

Main GPS frames (2)

- GPGSV : satellites in view
- A lot of other frames
    - From ship sensors (radar, sounder)
    - About waypoints and destination
    - Autopilot
    - Depth data
    - Engines
    - ...

GNSS Augmentation

- Enhance
  - Reliability
  - Availability
  - Accuracy/precision
- Based on
  - External information

GPS Errors

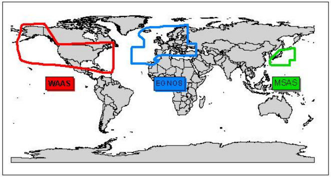
- Ephemeris
  - Global
- Atmosphere
  - Troposphere
  - Ionosphere
- Multipath
  - Varying

Augmentation Methods

- Data about errors
    - Clock drift
    - Ephemeris
    - Ionospheric delay
- Measurements about past errors
- Additionnal vehicle information

Augmentation systems

- Satellite Based :
  - WAAS : USA
  - EGNOS : Europe
  - MSAS : Japan
- Ground Based : DGPS
- Receivers must be adapted



Selective Availability Use

- GPS available for civilian use
  - Foreign military use too
  - DoD feared other armies might use GPS for guided weapons
- Selective Availability
  - Solution
  - Accurate enough for civilian use

Differential GPS (DGPS)

- Selective Availability
    - High error
- Other systems
    - LORAN, VOR
    - High cost (million $)
- GPS would replace all (spare money)
- DoD rejected requests from FAA (disable S/A)

DGPS : main ideas

- Selective Availability signal not changed frequently
  - Positioning error not varying (too much)
  - Uniform error on wide area
- Transmit the error to GPS users
  - Moreover, ionosphere errors correction
  - Final accuracy : 10 meters
- 1996 : limited use (DGPS stations in harbours)
- Then : most populated areas equipped

Principles

- Differential methods
    - User's location related directly to reference station's location
    - Station range up to 370 km
- Common errors corrected by difference
    - Simple difference
    - Double difference
    - Triple difference

Errors corrected

- Clock derivation
    - Between satellites and receiver
- Ephemeris (ground updates not perfect)
- Relativist effects (speed, gravitational field)
- Ionospheric error (signal slowed)
- Tropospheric error

Simple/Double/Triple Difference

- Observations on 1, 2 or 3 satellites
- Example on simple difference

$$R_1 - R_2 = d_1 - d_2 + c(dt_1 - dt_2) + e_{iono_1} - e_{iono_2} + e_{tropo_1} - e_{tropo_2} + e_{ephe_1} - e_{ephe_2} + e_{relat_1} - e_{relat_2} + e_{reste}$$

- With :
  - R : distance computed
  - D : true distance
  - dt : time difference
- Tropospheric, ephemeris and relativist errors are the same

Consequences

- DGPS deployement
  - GBAS
  - Cost for stations
  - Not deployed in rural environment
- Selective Availability
  - Useless because of DGPS
- To improve coverage
  - SBAS (WAAS, EGNOS, MSAS)

Conclusion

- DGPS developed as GBAS
- Evolutions to SBAS
    - WAAS
    - EGNOS
    - MSAS

Why enhance GPS ?

- FAA (Federal Aviation Administration)
  - ILS too expensive
  - Without WAAS, GPS not accurate enough to be used in precision approach
  - Main GPS error
    - Ionosphere
    - Move slowly
  - Monitoring and correcting ionospheric error to improve GPS accuracy

WAAS

- Wide Area Augmentation System
- Improves GPS
    - Accuracy
    - Integrity
    - Availability
- Main purpose
    - Aircrafts can rely on WAAS for all phases of flight, including precision approach
    - WAAS is certified SoL Cat. I

WAAS Ground Segment

- 38 Wide-area Reference Stations (WRS)
  - Collect information on GPS signals
- 3 Wide-area Master Stations (WMS)
  - Generate 2 corrections
    - Slow (errors varying slowly (ionospheric), ephemeris error)
    - Fast (errors varying fast (satellites instant location and clock error))
- 2 pairs of Ground Uplink Stations (GUS)
  - Transmission to WAAS space segment

WAAS Space Segment

- 2 commercial satellites
  - PanAmSat (Galaxy 15) and Telesat (Anik F1R)
  - Geostationnary orbit
    - Each hour on each day, same position
  - Broadcast WAAS + regular GPS messages

WAAS footprint

WAAS User Segment

- GPS and WAAS receivers
  - Can read both signals
- Uses fast and slow correction signals
  - Fast corrections are included immediatly in GPS calculation
  - Then, slow correction is applied
- Slow correction data updated every minute
  - 2 min for ephemeris and ionosphere data

WAAS stations

- Ground-based reference stations
  - In USA and Hawaii
- Master stations
  - Queue messages from reference stations
  - Send to geostationnary WAAS satellites
  - Every 5 seconds.
- WAAS sats.
  - Broadcast correction messages to Earth
  - WAAS-capable receivers can use it

WAAS objectives

- Accuracy
  - 95% with 7.6m accuracy or better (H+V)
- Integrity
  - Detect misleading data within 6.2 seconds
- Availability
  - Meet accuracy and integrity requirements
  - Unavailability 5 mins with WAAS, 4 hours else (each year)

WAAS benefits

- Addresses all of the navigation problem
- Highly accurate position, low cost (GPS receiver)
- Any airport can have precision approach
- Works between airports (reduce distances)
- Cost compared to ILS
  - Installation (50k$ for GPS, 1.5M$ for ILS)
  - Maintenance : saves 5 M$ each year

Limits

- Geostationnary orbit
  - Less than 10° for locations above 71.4° lattitude
  - Aircraft hardly lock WAAS signals
- WAAS receivers for aircraft cost at least 10 k$
- Cannot provide cat. II and III precision approach

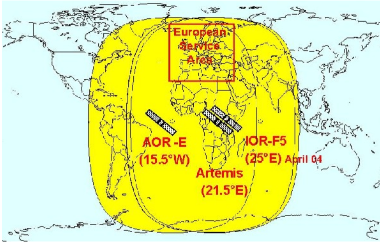
Future

- Improvements to aviation operations
    - Current : cat. I (above 200 feet)
    - Extension down to 200 feet
- Software improvements
    - Improve cover in Alaska
- Space Segment upgrade
    - Adding a satellite
    - Use L5

EGNOS

- European Geostationary Navigation Overlay Service
- 40 Ground stations
- Glonass and GPS compliant (Galiléo)
- 3 satellites
- EU and ESA fundings
- Launched in 2005

EGNOS


European
Service
Area
AOR -E
(15.5°W)
IOR-F5
(25°E) April 04
Artemis
(21.5°E)

Space Segment

- 3 satellites
    - INMARSAT Organization
        - IOR-W (PRN 126)
        - AOR-E (PRN 120)
    - ESA
        - Artemis (PRN 124)
        - Tests

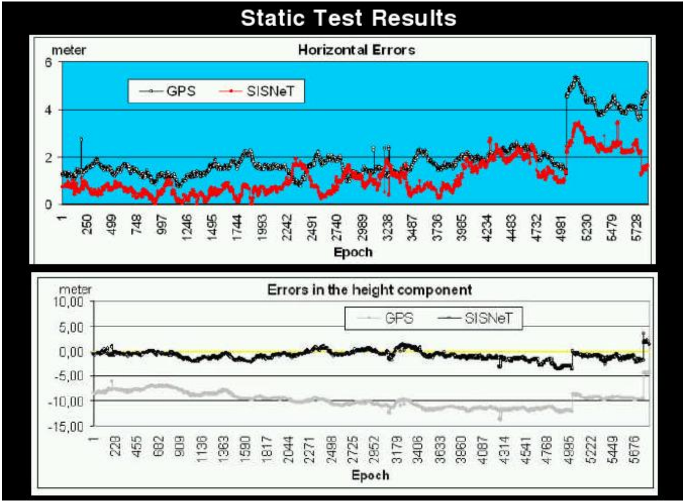
User Segment

- GPS receivers with compatibility
  - SiRF III
  - EGNOS service now available
- Available since July 2005
  - Accuracy : 2m
  - Availability : above 99%
- Used to track Tour de France cyclists
- Intended to be certified for SoL in 2010

SISNet

- Combining GNSS and Internet
- Give EGNOS SIS (Signal In Space) data through Internet (2G+)
  - GSM
  - GPRS
- No EGNOS receiver required
- 2006 : SISNet 3.1
- Now ?

EGNOS : Performances



GPS Military Applications

- Navigation
  - Night operations
  - Coordination of troops and supplies
- Target tracking
  - Weapon use GPS to track ground/air targets
  - Air-to-ground weapons
- Missile guidance

GPS Military Applications

- Search and Rescue
  - Downed pilots located w/ GPS receiver
- Recon and map creation
- Nuclear Detection
- In France
  - GNSS used in FELIN

GLONASS

- GLONASS : GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
- Former Soviet Union Satellite Navigation System
- Development began in 1976
- Constellation complete : 1995
- Fell into disrepair (collapse of Russian economics)
- 2001 : GLONASS restoration began

GLONASS purpose

- Replace Tsikada/Tsiklon system
  - Not instantaneous (poor accuracy)
- Ballistic missiles
- Peak efficiency (99.7%)
  - Positioning accuracy
    - 57-70m horizontal
    - 70m vertical
  - Velocity within 15cm/s
  - Time transfer within $1\mu s$

Orbital Characteristics

- Operationnal GLONASS constellation
  - 24 satellites
    - 21 for transmission
    - 3 for spare
  - 3 orbital plans
    - Every 120°
    - 8 sats. Each
    - 64.8° from Earth
    - Altitude : 19100 km
    - Orbital period 11h15

Orbital Characteristics

- Each plan has a 15° latitude displacement
  - One satellite at a time crosses equator
- With full constellation, everywhere $Number_{sat} \geqslant 5$
- Each satellite has a slot number (1 to 24)
  - 1 to 8 on first orbit, 9 to 16 on the second one, etc.
  - Every satellite passes on same point every 8th sideral day
  - 8 satellites on each orbit : every day, a satellite passes over the same point.

GLONASS coverage

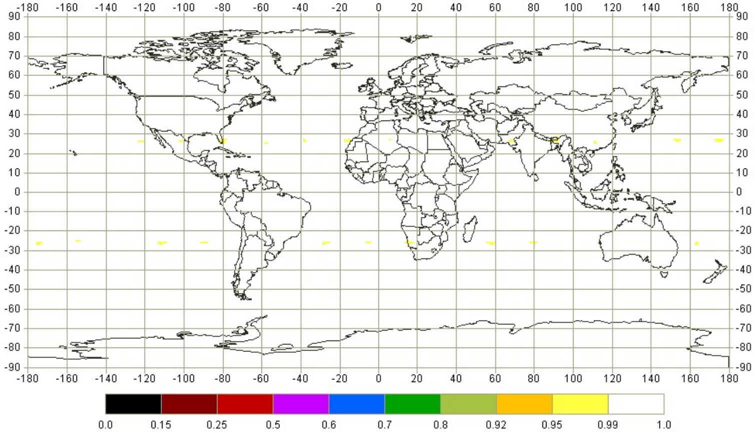


FIGURE: GLONASS coverage (2012).

Satellite Signals

- Two signals
  - Standard Precision (SP)
  - High Precision (HP) : obfuscated
- SP Signal
  - Same code
  - Different frequencies
    - 15 channels FDMA
    - Channels -7 to 7
    - L1 band : $1602 + n \times 0.5625$ MHz

Satellite Signals

- High Precision Signals
  - Frequencies of L1 $\times$ 10
  - Other details not disclosed
- L2 frequency
  - $1246 + n \times 0.4375$ MHz
  - Broadcast by all satellites except 1 (the oldest one)

Satellites

- Satellites are Uragan (Russian for hurricane) models
  - GRAU designation 11F654
  - Cosmos-*NNNN*
- 4 generations launched
  - 18 prototypes (1982-1985)
  - Type 1 : 6 Uragan (1985-86)
  - Type 2 : 14 Uragan-M (2001-2007)
  - Type 3 : Uragan-K (2009-n/d)

Ground Control

- Located in former USSR
- Moscow
  - Ground Control Center
  - Time Standards
- Telemetry and Tracking Stations
  - Saint Petersburg
  - Ternopol
  - Eniseisk
  - Komsomolsk-na-Amure

Receivers

- some Garmin eTrex
- Xiaomi Phone 2
- Sony Ericsson
- ZTE
- Huawei
- Samsung
  - Galaxy S3
  - Galaxy Note and Note II
- Apple
  - iPhone 4S, 5
  - iPad Mini (LTE only)
  - iPad III (LTE only)
- HTC
- LG
- Nokia
- Motorola

Current Status

- February 2009
  - 20 satellites
    - 19 operational
    - 1 under maintenance
- Coverage of Russia
  - Requires 18 satellites
  - Currently, 100% of Russian Federation

History

- From 1968 to 1969
  - Ministry of Defense, Academy of Science and Soviet Navy
- 1970 : requirements
- December 1976 : plan for developing GLONASS
- From 1982 to 1991 : USSR launched 43 GLONASS satellites + 5 test satellites
- 1991 : 12 functional satellites in 2 plans : limited usage

Decay

- 1991 : disintegration of USSR
- GLONASS development undertaken by Russian Federation
- Sept. 1994 : GLONASS declared operationnal
- Constellation completed in 1995
- 1995-2001 : Russia unable to maintain GLONASS
- April 2002 : 8 satellites, GLONASS useless

Restoration and Modernization

- Aug. 20, 2001
    - Special program
        - Restore GLONASS by 2011
        - Deploy 24 satellites
- April 2007 : Russia commited to accelerated launches
    - 8 satellites scheduled
    - Global coverage in 2009

Further developments

- 2007, prime minister Sergei Ivanov
  - 18 satellites available
  - 24 satellites in 2010
- December 2008
  - Russian Space agency stated
    - 30 satellites in 2011

Cooperation with Indian government

- Januar 2004 : joint venture with India's Space Agency
- Satellites built by Russia
  - Launched either from India or Russia
  - Coverage for both
- Russia and India share development cost for GLONASS-K satellites
- India obtained High Precision signal

Discussions with USA

- Benefits of changing GLONASS signals pattern to GPS ones
  - Receivers can use both
- GLONASS from FDMA to CDMA
  - Current status ?

Civilian signals available

- May 18, 2007, Vladimir Putin signed a decree
  - Open access to the GLONASS civilian navigation signals
    - Russian consumers
    - Foreign consumers
    - Free of charge
    - Without limitation
  - Directed Federal Space Agency to maintain, develop and enable GLONASS to civilian and commercial needs
- Mr. Putin acquired a GLONASS-enabled collar for his black labrador
  - Show the use of GLONASS in cattle monitoring

Galileo

- European GNSS
- Currently under development
- Decision taken in 2001
- Organization dedicated to Galileo
  - Private and public funds
  - Lots of administrations
    - Explanation for Galileo being late ?

Galileo short description

- Dependancy from GPS
  - Various restrictions
    - Positioning accuracy
    - Reliability
    - Continuity in some locations
    - Continuity for political reasons
- Decision to make Europe's own system

Galileo funding

- Under civilian control
  - Opposed to GPS/GLONASS
- 2 entities
  - European Union
  - European Space Agency
- ESNIS (European Satellite Navigation Industries)
  - Formerly Galileo Industries (GAIN)

Galileo funding

- ESNIS created in 2003
- Based in Bruxelles (Belgium)
- ESNIS was a failure
- Since the end of 2007 : direct funding from ESA
- Employment
    - 15-20000 jobs for development
    - 2000 jobs for maintenance

10 signals

- 6 for free services
- 2 for commercial service
- 2 for public regulated service (PRS)
- Used for 5 services

Open service

- Counterpart for current civilian GPS use
- 2 frequencies
  - 1164-1214 MHz
  - 1563-1591 MHz
- Using both : accuracy H $<$ 4m, V $<$ 8m
- Using only one : H $<$ 5m, V $<$ 35m
- Similar to GPS civilian accuracy
- No integrity

Commercial service

- Has a cost (paid to Galileo provider)
- Numerous services
    - Guarantee of service
    - Integrity
    - Signal continuity
    - Encrypted data broadcast through 2 signals
- Uses OS frequences + 1260-1300 MHz
- Accuracy < 1 m
- With ground signals, accuracy < 10 cm

Safety of Life service

- SoL service
  - Secure
  - Certified
- Airports precision approach must be SoL
- Used for services critical for life

Public Regulated Service

- For public services requiring
    - high accuracy
    - Signal quality
    - Transmission reliability
- Examples
    - Emergency services
    - Hazardous mat. transport
    - 2 encrypted signals and prevents
        - Malicious signals
        - jamming

Search and Rescue service

- Based on Cospas-Sarsat beacons (406 MHz)
- Locates all beacons
- Acknowledges distress signals
- Cospas-Sarsat
    - Worldwide SAR system
    - Based on old Argos

Galileo and EGNOS

- EGNOS : first european GNS
- Waiting for Galileo (30 satellites In 2014/2015)
  - Improve GPS and GLONASS
  - Will work with Galileo
- 2 consortiums building Galileo
  - InavSat
    - EADS, Thales, Inmarsat
  - Eurely
    - Alcatel, Finmeccanica, AENA, Hispasat

Cost

- Investment estimation : 3.4 GE
- Annual cost (operating, maintenance) : 220 ME
- Initially
  - 33% from public entities
  - 67% from iNavSat and Eurely
- Rivalry between partners : at least 5 years delay
- Now : 100% funded by public entities

Cooperation

- USA tried to cancel the project
  - Fear that enemies could use it for weapons
  - Avoid independance of EU in GNSS
  - Potential interferences issues with GPS
- Finally, they accept and participate in Galileo
- Agreement
  - Provide GPS M-code with civilian signals disabled
  - Provide PRS with open service disabled

Application fields

- Civilian domain
  - Commercial navigation
  - Aviation
- Military domain
  - Discussed (Galileo is a civilian program under civilian control)
  - PRS used by firemen and police
    - Why not by the armies ?

Galileo segments

- 4 segments
    - Space segment
    - Ground control segment
    - Ground mission segment
    - User test segment

Space segment

- 30 satellites on 3 orbits
- Altitude : 23616 km
- Each satellite
  - 700 kg
  - 1500 W solar panels
  - Several atomic clocks
  - Radio transmitter and receiver

Ground Control Segment

- In charge of satellite control
- Composed of
  - 3 control centers in Europe
  - 5 control stations for satellites
    - Command
    - Measure

Ground Mission Segment

- Create message broadcast by the satellite
- Detect anomalies
  - Alert users
- Performances measurements
- Composed of
  - 3 mission centers (with control stations)
  - 10 to 12 uplink stations
  - 40 world wide monitor stations

User Test Segment

- Real-time validation of Galileo
- Test User Segment (TUS) receiver
  - Prototype
  - Built by Thales

Current Status and Schedule

- 2 satellites
  - GIOVE-A (dec. 28, 2005)
  - GIOVE-B (apr. 27, 2008)
- GIOVE-A2
  - Ready to launch
- 2010
  - IOV (In Orbit Validation) : 4 satellites
- From 2010 to 2013
  - Full constellation (FOC : Full Operational Capability) : 26 satellites

Theoretical equations vs. reality

- Theory
  - 4 distances and 4 points give a position
  - exact distances
- Practically
  - distances are estimated
  - no exact value
- How to take care about the errors ?

Equations

- r_i is true distance between satellite i and mobile device,
- (x_M, y_M, z_M), (x_i, y_i, z_i) are coordinates of mobile device and satellite i,
- t_i is the traveling time (measured) of signal issued by satellite i,
- T is the clock error between mobile device and satellites,
- δ_i includes other errors (ionosphere, etc.) for signal transmitted by satellite i.

$$r_i = \sqrt{(x_M - x_i)^2 + (y_M - y_i)^2 + (z_M - z_i)^2}$$

and

$$r_i = c \cdot (t_i + T) + \delta_i$$ [1]

1. After this step, δ_i will be neglected.

Computation

We can write :

$$\sqrt{(x_M - x_i)^2 + (y_M - y_i)^2 + (z_M - z_i)^2} - c \cdot (t_i + T) = 0$$

T is a variable to solve too.
We can write $f_i(x_M, y_M, z_M, T) = \sqrt{(x_M - x_i)^2 + (y_M - y_i)^2 + (z_M - z_i)^2} - c \cdot (t_i + T) = 0$
therefore, we have an equation system :

$$\vec{f}(x_M, y_M, z_M, T) = \begin{pmatrix} f_1(x_M, y_M, z_M, T) \\ f_2(x_M, y_M, z_M, T) \\ \dots \\ f_N(x_M, y_M, z_M, T) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \dots \\ 0 \end{pmatrix}$$

Linearize

To solve the equation, we have to linearize. Let (x_0, y_0, z_0, T_0) an approximate solution and $\Delta x = x_M - x_0$ (same for Δy, Δz and ΔT). $\Delta \overrightarrow{u} = ^T (\Delta x, \Delta y, \Delta z, \Delta T)$. So we can write :

$$\overrightarrow{f}(x_0, y_0, z_0, T_0) + J \cdot \Delta \overrightarrow{u} + \overrightarrow{\varepsilon}^{\,2} = \overrightarrow{0}$$

where J is the jacobian matrix of $\overrightarrow{f}$ near (x_0, y_0, z_0, T_0) :

$$J = \begin{pmatrix} \frac{\partial f_1}{\partial x_M} & \frac{\partial f_1}{\partial y_M} & \frac{\partial f_1}{\partial z_M} & \frac{\partial f_1}{\partial T} \\ \frac{\partial f_2}{\partial x_M} & \frac{\partial f_2}{\partial y_M} & \frac{\partial f_2}{\partial z_M} & \frac{\partial f_2}{\partial T} \\ \dots & & & \\ \frac{\partial f_N}{\partial x_M} & \frac{\partial f_N}{\partial y_M} & \frac{\partial f_N}{\partial z_M} & \frac{\partial f_N}{\partial T} \end{pmatrix}_{(x_0, y_0, z_0, T_0)}$$

2. Will be neglected too.

Solving

- Iterative :
  - Solve linear system, get (x_1, y_1, z_1, T_1),
  - Replace in first non linear equation, and solve again,
  - until convergence.
- Try it (2D) with : $A(1,1)$, $B(10,11)$, $C(1,9)$, $AM = 12.83$, $BM = 1.1$ and $CM = 9.16$
- How do you solve with another point $D(-4,8)$ so that $DM = 14.24$?

Thank you for your attention

Questions ?