GNSS navigation

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Outline

- ✓Introduction
- ✓GNSS/INS integration
- ✓Quality parameters
- ✓GNSS
- ✓Errors

Introduction

GNSS positioning is totally different from INS techniques, which are based on inertial reactions.

GNSS positioning is based on distance measurements to satellites and geodetic reference systems (geometric and geodetic principles).

They mostly yield receiver/antenna coordinates in a well-defined terrestrial reference system with a standard frequency of 1 Hz*

GPS has continously evolved and now is the positioning and navigation system more simple, accurate and affordable for all type of users.

Example $\rightarrow$ *smarts phones* are equipped with GPS
Example $\rightarrow$ LEO satellites have on-board GPS receivers

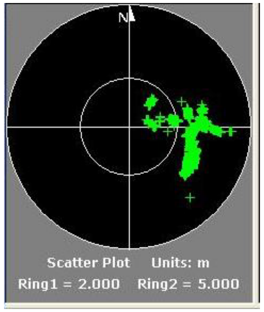
Introduction

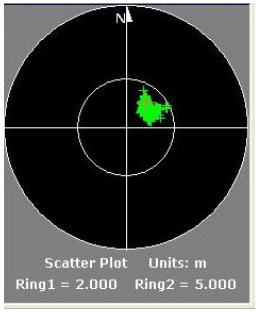
GNSS position can be determined using different methods:

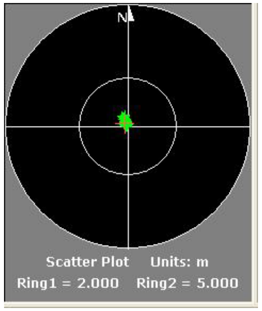
✓dynamic/kinematic (static)

✓Absolute /relative.

Depending on the type of receiver, observables, and processing strategies the coordinates of a moving object can be determined with a precision ranging from some m (≈ 5 m) to some cm (≈ 1 cm).







Introduction

With such wide applicability, GNSS could be seen as the unique system needed. Why should one bother with any other kind of system, like the INS?

Systems additional to GNSS are required when:

Accuracy and reliability are concerned (aircraft traffic control, approach and landing systems, collision avoidance systems, etc.)

GNSS are not available (mining, tunnels, submarines, vehicles in shadowed environments, like city canyons, etc.)

Attitude is mandatory (image-georeferencing, robotics, etc.)

Even so, many commercial and private aircrafts, as well as ships and boats now use GNSS as a primary navigation system.

Most usual scheme

- ✓dynamic/kinematic solutions
- ✓NMEA format
- ✓uncoupled GNSS/INS integration

NMEA 0183 protocol

NMEA format (standard)
Example → document NMEA0183.pdf

The NMEA 0183 Protocol

```
$GPGGA,114650.00,3928.76869,N,00020.34111,O,1,06,1.9,61.90,M,,,,*30
$GPGGA,114651.00,3928.76869,N,00020.34111,O,1,06,1.9,61.92,M,,,,*33
$GPGGA,114652.00,3928.76869,N,00020.34111,O,1,06,1.9,61.95,M,,,,*37
$GPGGA,114653.00,3928.76869,N,00020.34110,O,1,06,1.9,62.01,M,,,,*39
```

NMEA 0183 protocol

Proprietary NMEA Leica, Trimble,….
Example → document NMEA-0183-Trimble.pdf

PTNL,GGK (Time, Position, Position Type, and DOP)

The PTNL,GGK message structure is:

$PTNL,GGK,172814.00,071296,3723.46587704,
N,12202.26957864,W,3,06,1.7,EHT-6.777,M*48

```
$RTGGK,150257.0,121707,3928.764979,N,00020.258639,W,3,05,03.2,57.306,M*2
$RTGGK,150258.0,121707,3928.764980,N,00020.258638,W,3,05,03.2,57.310,M*2
$RTGGK,150259.0,121707,3928.764979,N,00020.258639,W,3,05,03.2,57.314,M*2
$RTGGK,150300.0,121707,3928.764979,N,00020.258638,W,3,05,03.2,57.302,M*2
$RTGGK,150301.0,121707,3928.764975,N,00020.258639,W,3,05,03.2,57.308,M*2

$RTGGK,151936.0,121707,3928.769111,N,00020.341403,W,2,05,03.1,57.266,M*2
$RTGGK,151937.0,121707,3928.768784,N,00020.340927,W,2,05,03.1,57.277,M*2
```

GNSS/INS implementation options

- There are three principal options for implementing an integrated GNSS/INS system:

- Uncoupled integration (open-loop mechanization) $\rightarrow$ the respective sensors perform a preprocessing of the position, velocity and time (GNSS), and position, velocity and attitude (INS)

- Loosely coupled integration $\rightarrow$ the respective sensors still perform a preprocessing, but the INS sensor errors are calibrated using a Kalman filter algorithm

- Tightly coupled integration (closed-loop mechanization) $\rightarrow$ is based on a centralized processing of the raw measurement data of the subsystems (pseudo-ranges and carrier phases for GNSS; specific-force and angular rates for INS). Ins sensors are calibrated within the centralized Kalman filter, and a velocity aiding feedback link is established towards the GNSS receiver.

GNSS/INS integration

Uncoupled

GNSS/INS integration

Tightly coupled integration

SPAN® GNSS Inertial Systems

NovAtel's SPAN® technology tightly couples our OEM precision GNSS receivers with robust Inertial Measurement Units (IMUs) to provide reliable, continuously available, position, velocity and attitude—even through short periods of time when satellite signals are blocked or unavailable.

SPAN Receivers

SPAN capable GNSS receivers including board level and board + enclosure products

SPAN Combined Systems

Compact, single enclosure GPS/INS system

GNSS/INSS integration

Tightly coupled integration

xsens

MTi-G

ADVANCED NAVIGATION

Quality parameters

US Federal Radionavigation Plan
International Maritime Organization
European Commision

The performance of a navigtion system is characterized by a number of statistical quality parameters:

Accuracy

Statistical measure that provides the degree of conformance between the estimated or measured parameter (e.g. position,…) of an object at a given time and the true parameter. It is usually presented Se as a statistical measure of the error together with a confidence interval (e.g. 95%).

Three types of accuracy are distiguished: Predictable or absolute, repeatable or precision (accuracy with which a user can return to a position whose coordinates have been determined at a previous time), and relative (to that of another user using the same system at the same time).

Accuracy = UERE * DOP

Quality parameters

Availabilty

Measure of the percentage of time during which the systems performs within its coverage area under specified condictions.

e.g. the receiver provides the required level of accuracy, integrity, and/or continuity.

Capacity

Nunber of users which can use a navigation system simultaneously.

Continuity

Ability of a system to perform a function without nonscheduled interruptions during an intended operation (e.g. landing phase of an aircraft) → Continuity risk.

Quality parameters

Coverage

That surface area or space volume where the performance of the system is adequate to permit the user to determine a position to a specified level of accuracy.

Integrity

The measure of the trust that can be placed in the correctness of the information provided by a navigation system.

It is the ability of a navigation system to provide timely warnings to the users when the system should not to be used:

Integrity risk: the probability of providing incorrect information without warning the user in the given period of time.

GNSS constellations

Currently there are three global systems:

GPS, GLONASS, GALILEO y COMPASS (BeiDou2)

OPERATIVE

UNDER DEPLOYMENT

Since technical specifications change over time in order to improve the systems, it is difficult to give a detailed description.

GNSS basics

Compatibility → refers to the ability of two services to be used separately or together without interfering with each individual service or signal.

Interoperatibility → refers to the ability to use two services together to achieve better performances at user level.

The different global systems has been designed to be compatible.

Nonetheless, an increasing number of agreements between the operators guarantees the interoperatibility of systems and signals.

Signals have been specified to be in common between the systems, though some signals have intentionally been separated to avoid common mode failures.

GNSS basics

Combined solution → the systems has been intentionally designed to use different reference frames, in order to avoid common mode failures and, thus, to increase the integrity of combined solutions.

In practice → different coordinate and time systems are not a major problem (e.g. for navigation purposes some can be considered similar and for precise applications a Helmert transformation can be applied)

The trend is to employ receivers that are able to use a combination of signals and services so that a better coverage is obtained even under non-favourable environments.

Although the technical specifications differs, fundamental theoretical aspects are similar.

GPS

CONSTELLATION: 24 satellites , 20.200 km, quasi-circular orbits, 6 orbital planes (55º). Expected: 27 satellites in 3 planes.

Carrier wave	Frequency	Wavelength
$L1$	1575.420 MHz	19.0 cm
$L2$	1227.600 MHz	24.4 cm
$L5$	1176.450 MHz	25.5 cm

Tabla 4.2: Carrier waves used by GPS

Codes: C/A, P1(Y1), M1, L1C, P2(Y2), M2, L2C, L5C.

Standard C/A positioning accuracy (usually~ 5 m)

Average after 24 h (95%) $\Rightarrow$ $\boxed{\begin{array}{l}\sigma_H \leq 13\ m \\ \sigma_V \leq 22\ m\end{array}}$

GPS

REFERENCE SYSTEM: WGS84

Parameter	Value	Description
a	6378137.0 m	semajor axis
f	1/298.257223563	flattening
ω_e	$7292115 \times 10^{-11}\ rad\, s^{-2}$	Earth's angular rate
μ	$3986004.418 \times 10^{8}\ m^{3}\ s^{-2}$	gravitational constant

Tabla 4.1: Fundamental parameters of the WGS84 reference system

Current version of the WGS84 is practically aligned to ITRF05.

GLONASS

CONSTELLATION: 24 satellites , 19.100 km, quasi-circular orbits, 3 orbital planes (64.8º).

Carrier wave	Frequency	Wavelength
$G1$	1602.000 MHz	18.7 cm
$G2$	1246.000 MHz	24.1 cm
$G5$	1204.704 MHz	24.9 cm

Tabla 4.5: Carrier waves used by GLONASS

Codes: C/A, P.

Standard C/A positioning accuracy (95%)

$$13m \leq \sigma_H \leq 100m$$
$$22m \leq \sigma_V \leq 156m$$

GLONASS

SISTEMA DE REFERENCIA: PZ-90 (PE-90)

Parameter	Value	Description
a	6378136.0 m	semimajor axis
f	1/298.257839303	flattening
ω_e	$7292115\ \times 10^{-11}\ rad\, s^{-2}$	Earth's angular rate
μ	$3986004.4\ \times 10^{8}\ m^3\ s^{-2}$	gravitational constant

Tabla 4.3: Fundamental parameters of the PZ-90 reference system

From 1998 to 1999 the project IGEX-98 analyzed PZ-90 and ITRF97 resulting the following transformation parameters

(Tz = 0,9 m, Rz = −0,354”)

RTCM-SC 104 v2.3 recommends to use Rz = −0,343”
Transformation consistency ~ 1 m.

Galileo

CONSTELLATION: 30 satellites , 23.200 km, quasi-orbital orbits, 3 orbital planes (56º).

Carrier wave	Frequency	Wavelength
$E1$	1575.420 MHz	19.0 cm
$E6$	1278.750 MHz	23.4 cm
$E5$	1191.795 MHz	25.2 cm
$E5a$	1176.450 MHz	25.5 cm
$E5b$	1207.140 MHz	24.8 cm

Tabla 4.9: Carrier waves used by Galileo.

Codes: E1A, E1B, E1C, E6A,E6B, E6C, E5a-I, E5a-Q, E5b-I y E5b-Q

Integrity improved!

Galileo

REFERENCE SYSTEM: GTRF

Parameter	Value	Description
a	6378137.0 m	semimajor axis
f	1/298.257222101	flattening
ω_e	$7292115 \times 10^{-11}\, rad\, s^{-2}$	Earth's angular rate
μ	$3986005.000 \times 10^{8}\, m^{3}\, s^{-2}$	gravitational constant

Tabla 4.8: Fundamental parameters of the GTRF reference system

Especification: the difference between GTRF coordinates and the most recent ITRF coordinates have to be below 3 cm (2σ).

The Galileo Geodetic Reference Service Provider (GRSP) is responsible for the GTRF realization.

IGS stations are used to align GTRF with ITRF.

Galileo

GTRF is periodically changed

GTRF	Date	Validity (years)
GTRF07v00	08/2007	0.69
GTRF07v01	11/2007	0.92
GTRF08v01	08/2008	1.69
GTRF09v01	08/2009	2.34

Tabla 4.6: First four GTRF realizations.

Galileo

GTRF(GTRF08v01) is practically aligned with ITRF05.

	T1	T2	T3	D	R1	R3	R3
Unid.	mm	mm	mm	ppb	mas	mas	mas
ITRF05	-0.1	-0.3	-0.2	0.08	0.004	0.002	-0.002
Error	0.2	0.2	0.2	0.03	0.008	0.008	0.008
Rates	-0.1	-0.1	0.0	0.03	0.002	0.000	0.000
Error	0.2	0.2	0.2	0.03	0.008	0.008	0.008

Tabla 4.7: Transformation parameters from GTRF(GTRF08v01) to ITRF05 (epoch 07:241)

COMPASS(BeiDou2)

CONSTELLATION: 27 satelites (MEO) , 21.500 km, quasi-circular orbits, 3 orbital planes (55º) + 5 stellites in geoestationary orbit (GEO) + 3 satellites in geosynchronous orbit (IGSO).

Carrier wave	Frequency	Wavelength
$B1$	1561.098 MHz	19.2 cm
$B2$	1207.140 MHz	24.8 cm
$B3$	1268.520 MHz	23.6 cm
$B4$	1575.420 MHz	19.0 cm

Tabla 4.11: Carrier waves used by BeiDou-2.

Some carrier waves coincide with those corresponding to Galileo.
Advantage in terms of compatibility.
Possible source of potential interferences.

COMPASS(BeiDou2)

REFERENCE SYSTEM: BDC

Parameter	Value	Description
a	6378137.0 m	semimajor axis
f	1/298.257222101	flattening
ω_e	$7292115 \times 10^{-11}\, rad\, s^{-2}$	Earth's angular rate
μ	$3986004.418 \times 10^{8}\, m^{3}\, s^{-2}$	gravitational constant

Tabla 4.10: Fundamental parameters of the Beidou-2 reference system.

The BDC reference system is aligned with the China Geodetic Coordinate System (CGCS), specifically the China Terrestrial Reference Frame 2000 (CTRF 2000) which in turn is consistent with the ITRF97 (época 2000.0).

The fundametal parameters are equal to those corresponding to GRS80, but the gravitational constant which is taken from the WGS84.

Observables

Pseudo-ranges

$$P_k^p(t_k) = \rho_k^p(t_k) + \left(c - \dot{\rho}_k^p(t_k)\right) dt_k - c\,dt^p + I_k^p(t_k) + T_k^p(t_k) + dm_k^p(t_k) + d^p + d_k + e_k^p(t_k)$$

Carrier phase (m)

$$\begin{aligned}\Phi_k^p(t) = {} & \rho_k^p(t_k) + \left[c - \dot{\rho}_k^p(t_k)\right] dt_k - c\,dt^p - I_{k,\Phi}^p(t_k) + T_k^p(t_k) + \delta m_{k,\Phi}^p(t_k) + \lambda N_k^p \\ & + \lambda\left[\Phi_k(t_0) - \Phi^p(t_0)\right] + \delta_k + \delta^p + \lambda \epsilon_k^p(t)\end{aligned}$$

Carrier phase (cycles)

$$\begin{aligned}\varphi_k^p(t) = {} & \tfrac{f}{c}\rho_k^p(t_k) + f\left[1 - \tfrac{\dot{\rho}_k^p(t_k)}{c}\right] dt_k - f\,dt^p - I_{k,\varphi}^p(t_k) + \tfrac{f}{c}T_k^p(t_k) + \delta m_{k,\varphi}^p(t_k) + N_k^p \\ & + \lambda\left[\varphi_k(t_0) - \varphi^p(t_0)\right] + \delta_{k,\varphi} + \delta_\varphi^p + \lambda \epsilon_k^p(t)\end{aligned}$$

Distance computation (ECEF)

Broadcast ephemeris (WGS84) as well as precise ephemeris (ITRS,IGS,..) provide the satellite's ECEF coordinates.

Introducing the receiver coordinates, the distance is computed

$$\rho_k^p(t) = \sqrt{\left(X^p\left(t-\tau_k^p\right)-X_k(t)\right)^2+\left(Y^p\left(t-\tau_k^p\right)-Y_k(t)\right)^2+\left(Z^p\left(t-\tau_k^p\right)-Z_k(t)\right)^2}$$

Since ECEF are not expressed in a inertial frame, the obtained distances have to be corrected due to the Earth's rotation during the signal transit time (~ 75 ms).

$$\vec{r}^{\,p} = R_3\left(\omega\tau_k^p\right)\vec{r}^{\,p}_{ECEF}\left(t-\tau_k^p\right)$$

Equation for kinematic positioning (carrier phase)

$$\Phi_{kl}^{pq}(t) = \rho_{kl}^{pq}(t) - \dot{\rho}_l^{pq}(t_l)\, dt_l - \dot{\rho}_k^{pq}(t_k)\, dt_k - I_{kl,\Phi}^{pq}(t) + T_{kl}^{pq}(t) + \delta m_{kl,\Phi}^{pq}(t) + \lambda N_{kl}^{pq} + \lambda \epsilon_{kl}^{pq}(t)$$

$$\Phi_{kl}^{pq}(t) = \Phi_{kl}^{q}(t) - \Phi_{kl}^{p}(t) = \Phi_l^{q}(t) - \Phi_k^{q}(t) - \Phi_l^{p}(t) + \Phi_k^{p}(t)$$

$$-\dot{\rho}_l^{pq}(t_l)\, dt_l + \dot{\rho}_k^{pq}(t_k)\, dt_k$$

$$T_{kl}^{pq}(t) = T_l^{q}(t) - T_k^{q}(t) - T_l^{p}(t) + T_k^{p}(t) \quad \left\{ \begin{array}{l} T_{kl}^{pq}(t) \approx 0 \\ 1\ cm < e_{trop} < 3\ cm \\ 3\ cm < \Delta h < 9\ cm \end{array} \right.$$

$$I_{kl}^{pq} \approx 0$$

Equation for kinematic positioning (carrier phase)

$$a_x^{pq}(t)\,dX + a_y^{pq}(t)\,dY + a_z^{pq}(t)\,dZ + \lambda N_{kl}^{pq} - k(t) = \lambda \epsilon_{kl}^{pq}(t)$$

$$k(t) = \left[\Phi_{kl}^{pq}(t) - \dot{\rho}_l^{pq}(t)\,dt_l - \dot{\rho}_k^{pq}(t)\,dt_k + T_{kl}^{pq}(t) - \rho_{kl}^{pq}\left(t, \vec{X}_l^{(0)}\right)\right]$$

$$\left|\frac{\partial \rho_{kl}^{pq}(t)}{\partial X}\right|_{\vec{X}_l^{(0)}} = -\left[\frac{X^p\left(t-\tau_l^p\right) - X_l^{(0)}}{\rho_l^p\left(t, \vec{X}_l^{(0)}\right)} - \frac{X^q\left(t-\tau_l^q\right) - X_l^{(0)}}{\rho_l^q\left(t, \vec{X}_l^{(0)}\right)}\right] = a_x^{pq}(t)$$

$$\left|\frac{\partial \rho_{kl}^{pq}(t)}{\partial Y}\right|_{\vec{X}_l^{(0)}} = -\left[\frac{Y^p\left(t-\tau_l^p\right) - Y_l^{(0)}}{\rho_l^p\left(t, \vec{X}_l^{(0)}\right)} - \frac{Y^q\left(t-\tau_l^q\right) - Y_l^{(0)}}{\rho_l^q\left(t, \vec{X}_l^{(0)}\right)}\right] = a_y^{pq}(t)$$

$$\left|\frac{\partial \rho_{kl}^{pq}(t)}{\partial Z}\right|_{\vec{X}_l^{(0)}} = -\left[\frac{Z^p\left(t-\tau_l^p\right) - Z_l^{(0)}}{\rho_l^p\left(t, \vec{X}_l^{(0)}\right)} - \frac{Z^q\left(t-\tau_l^q\right) - Z_l^{(0)}}{\rho_l^q\left(t, \vec{X}_l^{(0)}\right)}\right] = a_z^{pq}(t)$$

Kalman filtering $\rightarrow$ ambiguity determination on-the-move

Dynamic positioning

Absolute methods

- ✓ Code (SPP)
- ✓ Code + carrier phase (PPP)

Relative methods

- ✓ Code (DGPS)
- ✓ Code + carrier phase (RTK, RTK-VRS)

Dynamic positioning

Absolute

User Equivalent Range Error

$$\sigma_{UERE=\sqrt{\sigma_{dt^p}^2+\sigma_{eph}^2+\sigma_{iono}^2+\sigma_{trop}^2+\sigma_{mp}^2+\sigma_{dt_k}^2+\sigma_{noise}^2}}$$

Navigation solution error

$$\sigma_{SN=GDOP\times UERE}$$

GPS $\sigma_H(95\%) \approx 13\ m$

Galileo $\sigma_H(95\%) \approx 5\ m$

favourable environment

(no multipath)

Dynamic positioning

SPP (Standard point positioning)

favorable environment (no multipath)

GPS $$\sigma_H(95\%) \approx 13\ m$$

GLONASS (sligthly worst than GPS)

Galileo $$\sigma_H(95\%) \approx 5\ m$$

Dynamic positioning

PPP (Precise point positioning)

Pseudo-ranges, carrier phase, *iono-free* combination, and precise ephemeris

Static + final orbits + post-processing $\rightarrow$ cm

Dynamic + ultra-rapid ephemeris $\rightarrow$ 2-3 dm

They can be used to navigate (car, ship, even airplane)

$$\sigma_{UERE} = \sqrt{\sigma^2_{dt^p} + \sigma^2_{eph} + \sigma^2_{iono} + \sigma^2_{trop} + \sigma^2_{mp} + \sigma^2_{dt_k} + \sigma^2_{noise}}$$

Dynamic positioning

DGPS (Differential GPS)

GNSS diferential using code $\rightarrow$ 1-3 m

RTK (Real-Time Kinematic/Pahse/Ambiguities)

Traditional $\rightarrow$ 5 cm + 5 ppm

VRS $\rightarrow$ 5 cm + 5 ppm (lower repeatability)