2. GPS and GLONASS—Basic Facts

In 1973 the U.S. Department of Defense decided to establish, develop, test, acquire, and deploy a spaceborne Global Positioning System (GPS). The result of this decision is the present NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System). According to [*Wooden*, 1985]

> “ The NAVSTAR Global Positioning System (GPS) is an all-weather, space-based navigation system under development by the U.S. Department of Defense to satisfy the requirements for the military forces to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis. ”

From this definition it is clear that the primary goals for developing the GPS were of a military nature. But the U.S. Congress has allowed civilians to use this system with some restrictions. The civilian usage of the NAVSTAR GPS has developed enormously within the last two decades. With the elimination of SA (Selective Availability) on May 2, 2000, the usefulness of the system for civilian users was even more pronounced. One of the most important events for the high-accuracy civilian applications of GPS was the establishment of the *International GPS Service (IGS)* — [*Mueller and Beutler*, 1992; *Beutler*, 1992; *Beutler et al.*, 1999].

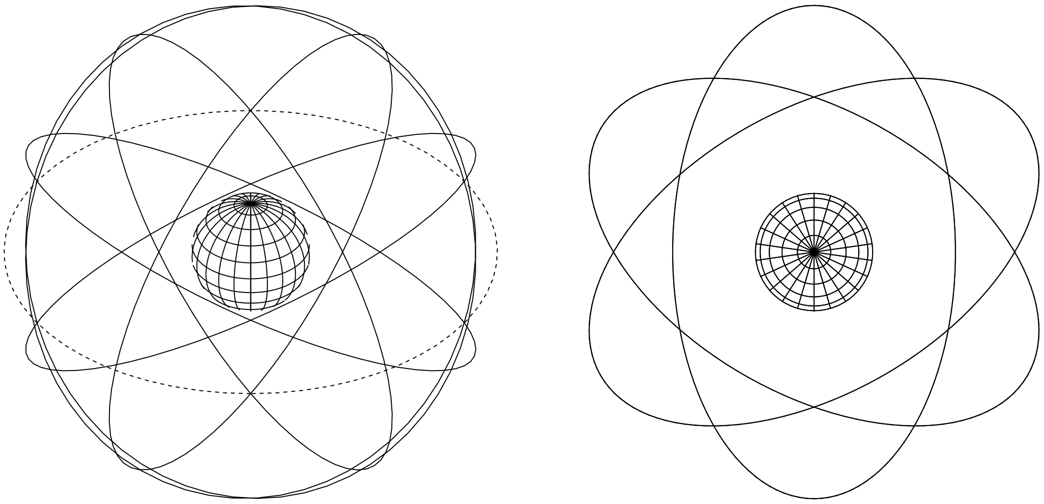
There are several other global positioning systems either operational or under development. However, NAVSTAR GPS has undoubtedly the greatest impact on the scientific community at present. Therefore, we use the term GPS as a synonym for NAVSTAR GPS. In this chapter we present some basic facts concerning the GPS.

Starting with Version 4.2 the *Bernese GPS Software* is also capable of processing GLONASS data [*Habrich*, 1999]. GLONASS stands for (GLObal NAvigation Satellite System). It is the Russian counterpart of the GPS system. In Section 2.4 we compare the GLONASS to the GPS.

2.1 GPS Satellites and Their Constellation

The constellation of the GPS was subject to several changes due to budgetary considerations. The present *full constellation* provides global coverage with four to eight simultaneously observable satellites above 15° elevation. This is accomplished by 24 satellites (in January 2001, 28 satellites were active). The satellites are located in six orbital planes on almost circular orbits with an altitude of about 20 200 km above the surface of the Earth, inclined 55° with respect to the equator and with orbital periods of approximately 11 hours 58 minutes (half a sidereal day). Consequently, almost identical Earth-satellite configurations are repeated 4 minutes earlier on consecutive days.

The distribution of the GPS satellites over the six orbital planes is listed in Table 2.1. The first GPS satellite PRN 4 (Pseudo-Random Number — see below) was launched on February 22, 1978. PRN 4 was the first in a series of 11 so-called Block I satellites. The Block I satellites had an inclination of about 63° with respect to the Earth's equator. The test configuration was optimized for the North American region in the sense that four or more satellites could be observed there for a considerable fraction of the day. The test configuration was not optimal in other parts of the world. Today, all Block I satellites are deactivated.



(a) Viewed from a latitude of $\phi = 35^{\circ}$.

(b) Viewed from a latitude of $\phi = 90^{\circ}$.

Figure 2.1: GPS orbits (Earth and orbital planes in scale).

Table 2.1: GPS constellation status (21-Nov-2000).

Plane	SVN	PRN	Block	Launch	Plane	SVN	PRN	Block	Launch
A-1	39	09	IIA	93-06-26	D-1	24	24	IIA	91-07-04
A-2	25	25	IIA	92-02-23	D-2	46	11	IIR	99-10-07
A-3	38	08	IIA	97-11-06	D-3	17	17	II	89-12-11
A-4	27	27	IIA	92-09-09	D-4	34	04	IIA	93-10-26
A-5	19	19	II	89-10-21	D-5	15	15	II	90-10-01
B-1	22	22	IIA	93-02-03	E-1	51	20	IIR	00-05-11
B-2	30	30	IIA	96-09-12	E-2	21	21	II	90-08-02
B-3	13	02	II	89-06-10	E-3	40	10	IIA	96-07-16
B-4	35	05	IIA	93-08-30	E-4	23	23	IIA	90-11-26
B-5	44	28	IIR	00-07-16					
C-1	36	06	IIA	94-03-10	F-1	41	14	IIR	00-11-10
C-2	33	03	IIA	96-03-28	F-2	26	26	IIA	92-07-07
C-3	31	31	IIA	93-03-30	F-3	43	13	IIR	97-07-23
C-4	37	07	IIA	93-05-13	F-4	32	01	IIA	92-11-22
					F-5	29	29	IIA	92-12-18

The GPS satellites provide a platform for radio transmitter, atomic clocks, computers, and various equipment used for positioning and for a series of other military projects (e.g., atomic flash detection). The electronic equipment of the satellites allows the user to operate a receiver to measure quasi-simultaneously topocentric distances to more than three satellites. Each satellite broadcasts a message which allows the user to recognize the satellite and to determine its position in space for arbitrary time epochs. The satellites are equipped with solar panels for power supply, reaction wheels for attitude control, and a propulsion system for orbit adjustments. The operational constellation is realized through the Block II, Block IIA, and Block IIR satellites. The first Block II satellite was launched in February 1989. Today, a full constellation of at least 24 satellites is available (28 satellites in January, 2001).

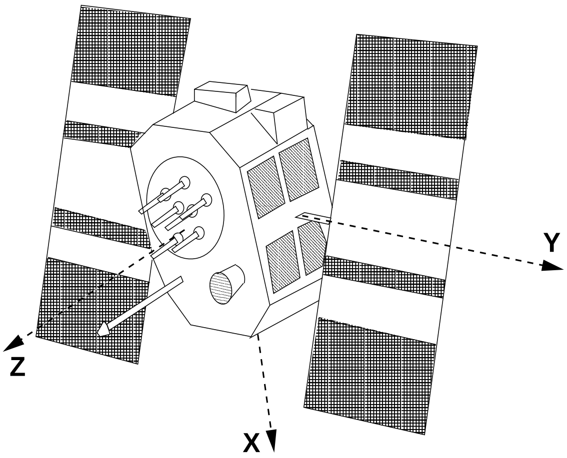


Figure 2.2: GPS Block II satellite and satellite-fixed coordinate system.

2.2 The Satellite Signal

All signals transmitted by the satellite (see Table 2.2) are derived from the fundamental frequency f_0 of the satellite oscillator.

Table 2.2: Components of the satellite signal.

Component	**Frequency** [MHz]		
Fundamental frequency	f_0	=	10.23
Carrier L_1	$f_1 = 154\, f_0$	=	1575.42 ($\lambda_1 \doteq 19.0$ cm)
Carrier L_2	$f_2 = 120\, f_0$	=	1227.60 ($\lambda_2 \doteq 24.4$ cm)
P-code $P(t)$	f_0	=	10.23
C/A-code $C(t)$	$f_0/10$	=	1.023
Navigation message $D(t)$	$f_0/204600$	=	$50 \cdot 10^{-6}$

The two sinusoidal carrier frequencies f_1 and f_2 (corresponding wavelengths $\lambda_1 \approx 19$ cm and $\lambda_2 \approx 24$ cm) are modulated with the codes and the navigation message to transmit information such as the readings of the satellite clocks, the orbital parameters, etc. The so-called biphase modulation is used as shown in Figure 2.3:

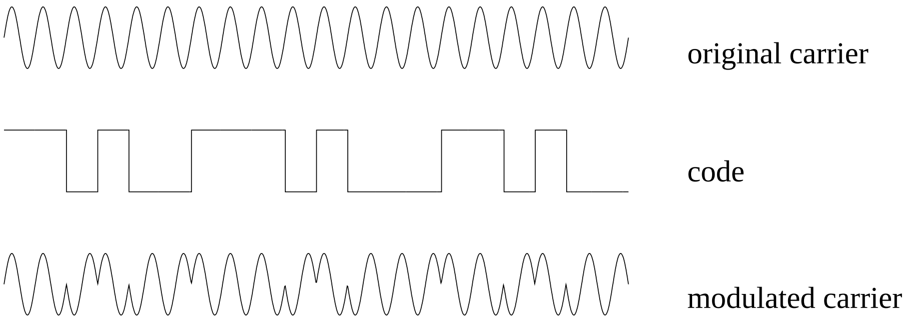


Figure 2.3: Biphase modulation of the GPS signal.

The codes $P(t),\ C(t)$, and the navigation message $D(t)$ consist of sequences with two states $+1$, -1, where according to [*Baueršíma*, 1982] the resulting signals may be described as

$$\begin{aligned} L_1(t) &= a_p\, P(t)\, D(t)\, \cos 2\pi(f_1 t) + a_c\, C(t)\, D(t)\, \sin 2\pi(f_1 t) \\ L_2(t) &= b_p\, P(t)\, D(t)\, \cos 2\pi(f_2 t) \end{aligned} \tag{2.1}$$

where a_p, a_c and b_p are the amplitudes of the signals which are not of interest in our context.

Pseudo-Random Codes

The two codes $P(t),\ C(t)$ consist of so-called pseudo-random noise (PRN) sequences. The generation of these sequences is based on hardware devices called tapped feedback shift registers.

The C/A-code (Coarse-Acquisition or Clear-Access) is generated by the combination of two 10-bit tapped feedback shift registers where the output of both registers are added again by binary operation to produce the code sequence. A unique code is assigned to each satellite, the sequence has a length of 1023 bits and because of the basic frequency of 1.023 MHz it repeats itself every millisecond. The time interval between two subsequent bits ($\approx 10^{-6}$ s) approximately corresponds to 300 meters.

The generation of the P-code (Precise or Protected) is similar, but the length of the resulting sequence is approximately $2.3547 \cdot 10^{14}$ bits corresponding to a time span of about 266 days. The total code is partitioned into 37 one-week segments. One segment is assigned to each satellite (which defines the *PRN number* of the satellite). The P-code repeats itself every week. The time interval between subsequent bits is 10 times smaller than in the case of the C/A-code. Therefore the accuracy is approximately 10 times higher than for the C/A-code. The P-code may be encrypted. This procedure is called *Anti-Spoofing* (AS) and converts the P-code to the Y-code which is only usable when a secret conversion algorithm is accessible to the receiver. Since 1995 the encryption is turned on for all satellites.

The Navigation Message

The navigation message is 1500 bits long and contains information concerning the satellite clock, the satellite orbit, the satellite health status, and various other data. The message is subdivided into five *subframes*. Each subframe contains 10 words. The first word is the so-called *telemetry word* (TLM) containing a synchronization pattern and some diagnostic messages. The second word of each subframe is the *hand-over word* (HOW). This word contains among others the so-called *Z-count* which gives the number of 1.5 s intervals since the beginning of the current GPS week. This number and the P-code give the reading of the satellite clock at signal transmission time. The first subframe contains various flags and the polynomial coefficients which define the satellite clock correction (see Table 2.3).

Table 2.3: Broadcast clock parameters.

Parameter	**Explanation**
Code-Flag L_2	Indicator for C/A or P-code on L_2
Week No.	GPS week
L_2-P-Data-Flag	Indicator for data on L_2-P-code
SV-Accuracy (URA)	Measure for distance accuracy
SV-Health	Satellite health indicator
T_{GD}	Group delay difference L_1-L_2-P-Code
AODC	Age of clock data
t_{0c}	Reference epoch
$a_0,\ a_1,\ a_2$	Clock correction polynomial coefficients

The second and the third subframe contain the broadcast ephemerides of the satellite (see Table 2.4).

Table 2.4: Broadcast ephemerides.

Parameter	Explanation
AODE	Age of ephemerides data
t_e	Ephemerides reference epoch
$\sqrt{a},\ e,\ M_0,\ \omega_0,\ i_0,\ \ell_0$	Keplerian parameters at t_e
$\mathrm{d}\,n$	Mean motion difference
$\mathrm{d}\,i$	Rate of inclination angle
$\mathrm{d}\,\Omega$	Rate of node's right ascension
$C_{uc},\ C_{us}$	Correction coeff. (argument of perigee)
$C_{rc},\ C_{rs}$	Correction coeff. (geocentric distance)
$C_{ic},\ C_{is}$	Correction coeff. (inclination)

Using the broadcast ephemerides the Earth-fixed geocentric coordinates of the satellites may be computed according to the formulas given in [*Dierendonck et al.*, 1978]. The fourth and the fifth subframe contain data for military use, information on the ionosphere, and so-called almanac data (low-accuracy orbits of all the GPS satellites).

The GPS user may decide whether to use the broadcast ephemerides or the precise ephemerides (produced by the IGS) for processing. The broadcast ephemerides are available in real time, but they have an accuracy of "only" several meters. The precise ephemerides have an accuracy of several centimeters and they are available with a delay of about two weeks for final products, of below one day for so-called rapid products (see Chapter 7).

The satellite clock corrections are required for processing. The accuracy of this information in the broadcast message was artificially degraded (Selective Availability, SA) for non-privileged users until May 2, 2000, when the degradation was disabled by the U.S. The effect of SA was fully eliminated in geodetic applications when only relative positions of receivers were estimated. The IGS precise orbits contain highly accurate satellite clock corrections, too.

2.3 Signal Processing

The receivers contain elements for signal reception and signal processing (antenna, pre-amplifier, radio frequency (RF) section, microprocessor, storage device, control device, and power supply). After signal input from the antenna, the signals are discriminated, i.e., separated into satellite-specific signals. Usually this is achieved through the C/A-codes which are unique for each satellite. The basic elements of the RF section are oscillators to generate a reference frequency, filters to eliminate undesired frequencies, and mixers. The *pseudorange measurements* are achieved as follows: a reference carrier is generated in the receiver and then modulated with a copy of the known PRN code. This modulated reference signal is correlated with the received satellite signal. Neglecting the receiver and satellite clock errors (see Chapter 9) this correlation gives directly the travel time τ (or, multiplied by the velocity of light c, the so-called pseudorange $c\,\tau$).

The *phase measurements* are based on processing the reconstructed signal carriers. This signal is usually obtained by the code demodulation technique using the correlation between the received signal and the signal copy generated by the receiver. Other techniques must be used for the L_2 phase in C/A-code receivers or for both phases in the case of the codeless receiver. One technique is the so-called squaring technique, where the received signal is multiplied with itself and hence all "$\pm\pi$ modulations" are removed. The result is the unmodulated squared carrier with half the period. From this squared carrier a sine wave is derived with a wavelength of only half the wavelength of the original signal. Another possibility is the so-called cross-correlation technique.

The receiver records the signal at time t. This signal was transmitted by the satellite at time $t-\tau$ (see also Chapter 9). At time $t-\tau$ the phase of the satellite oscillator equals $\phi^i(t-\tau)$ and at time t the phase of the receiver oscillator equals $\phi_k(t)$. The receiver thus compares the following two signals:

$$y^i = a^i \ \cos\ 2\pi\phi^i(t-\tau) \quad \text{and} \quad y_k = a_k \ \cos\ 2\pi\phi_k(t)\ , \tag{2.2}$$

where a^i and a_k are the amplitudes of the signals. Multiplying these two signals we obtain:

$$y = y^i y_k = \frac{a^i a_k}{2}\Big\{\cos 2\pi\Big[\phi_k(t)-\phi^i(t-\tau)\Big] + \cos 2\pi\Big[\phi_k(t)+\phi^i(t-\tau)\Big]\Big\}\ . \tag{2.3}$$

After applying a low-pass filter, the high frequency part $\phi^i(t-\tau)+\phi_k(t)$ is eliminated and (compare Chapter 9)

$$\psi^i_k = \phi_k(t) - \phi^i(t-\tau) + n^i_k \tag{2.4}$$

may be measured. The accuracy of the phase measurements is about 1–3 mm, but the exact number of integer wavelength between the satellite and the receiver n^i_k is not known at the time of the first measurement. The unknown integer number of cycles n^i_k to be added to the phase measurement to get a pseudorange is called the *initial phase ambiguity* (see also Chapter 9). This phase ambiguity has the same value as long as the receiver keeps lock on the phase transmitted by the satellite.

2.4 The GLONASS System

2.4.1 GLONASS Satellites and Their Constellation

The GLONASS (GLObal NAvigation Satellite System or more precisely "GLObalnaya NAvigatsionnaya Sputnikovaya Sistema") is like the GPS a satellite-based radio-navigation system which provides the user with positioning and timing information. It is operated by the Ministry of Defense of the Russian Federation. The nominal constellation of the GLONASS consists of 24 satellites, equally distributed in 3 orbital planes, which are separated by 120^o in the equatorial plane.

The GLONASS satellites are orbiting at a height of 19'130 km, i.e., about 1000 km below the GPS satellites (20'200 km). This results in an orbital period of 11 h 15 min 44 s corresponding to $8/17$ of a sidereal day. Whereas the orbital periods of the GPS satellites are in deep 2:1 resonance with Earth rotation, the GLONASS satellites do not show such effects: the GLONASS satellites perform $2\frac{1}{8}$ revolutions per sidereal day, whereas the GPS satellites perform 2 revolutions per one sidereal day. Assuming a full constellation the GLONASS geometry repeats itself every sidereal day with each individual satellite shifted for 45^o within the orbital plane. After eight sidereal days, each GLONASS satellite has completed 17 orbital revolutions and appears at the same position with respect to an Earth-fixed system. The ground track of one GLONASS and one GPS satellite are compared in Figure 2.5. Whereas the ground track of a GPS satellite repeats every sidereal day the ground track of a GLONASS satellite repeats only after eight sidereal days. Furthermore, Figure 2.5 shows that the higher inclination of the GLONASS orbital planes (i=64.8^o) leads to an improved coverage of the high latitude regions compared to the GPS (i=55^o).

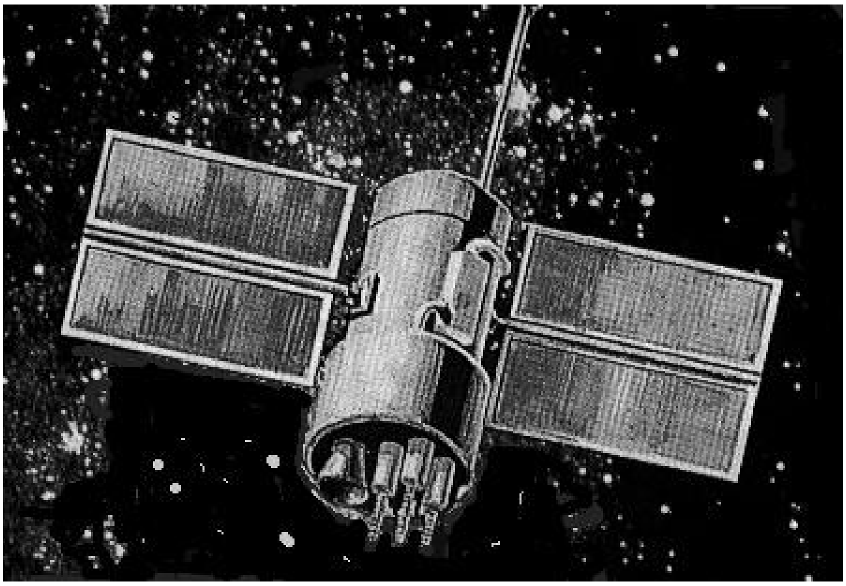


Figure 2.4: GLONASS satellite.

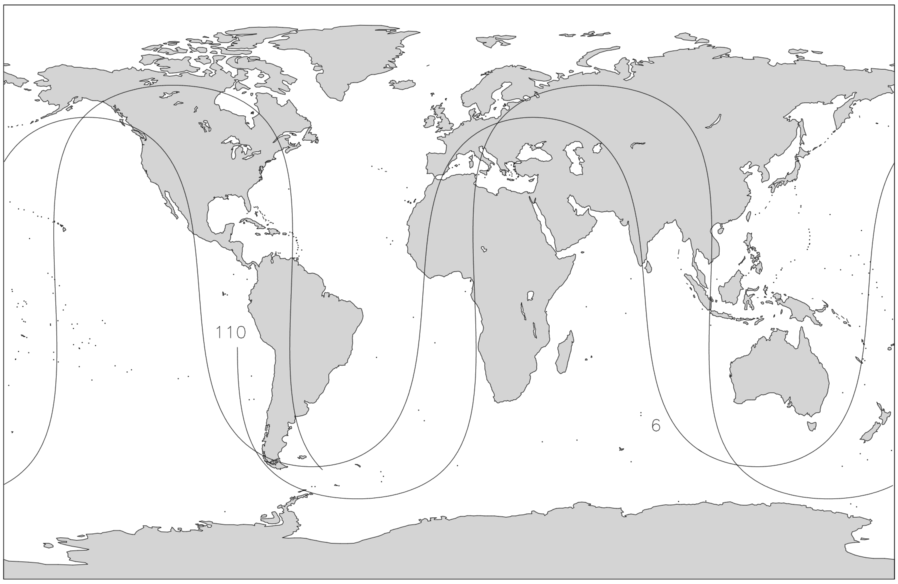


Figure 2.5: Ground track of GLONASS satellite (110) compared to the ground track of GPS satellite (6) for the time interval of one sidereal day.

The main differences between the GLONASS and the GPS are summarized in Table 2.5.

Table 2.5: Comparison of the GLONASS with the GPS.

	GLONASS	**GPS**
Nominal number of satellites	24	24
Operational satellites (end of 2000)	9	28
Orbital planes	3 (separated by 120^o)	6 (separated by 60^o)
Satellites per orbital plane	8 (equally spaced)	4 (unequally spaced)
Orbital radius	25'510 km	26'560 km
Inclination of orbital planes	64.8^o	55^o
Revolution period	$\sim$ 11 h 16 min	$\sim$ 11 h 58 min
Nominal eccentricity	0	0
Ground track repeatability	after eight sidereal days	after one sidereal day
Constellation repeatability	$\sim$ 23 h 56 min	$\sim$ 23 h 56 min
Signal separation technique	FDMA	CDMA
Carrier L1	1602.5625 – 1615.5 MHz	1575.42 MHz
Carrier L2	1246.4375 – 1256.5 MHz	1227.60 MHz
C/A-code (L1)	0.511 MHz	1.023 MHz
P-code (L1, L2)	5.110 MHz	10.23 MHz
Reference system	PZ-90	WGS-84
Time reference	UTC (SU)	UTC (USNO)

The future of the GLONASS seems uncertain due to economic problems. The number of operational satellites was steadily decreasing over the past few years. The launch of three new GLONASS satellites in December 1998 was the first launch after a lapse of 3 years. Afterwards it took two more years until the launch of three more GLONASS satellites in October, 2000. At present (December 2000) a total of nine GLONASS satellites are operational and provide signals on both frequencies.

Information on the latest status of the GLONASS may be found on the web page of the Coordination Scientific Information Center: `http://www.rssi.ru/SFCSIC/nagu.txt`.

2.4.2 The Signals of the GLONASS Satellites

The basic observations of the GLONASS are very similar to the observations of the GPS: C/A-code on L1, P-code on L1 and L2, and carrier phase measurements on L1 and L2. A big advantage of the GLONASS with respect to the GPS was the absence of the Selective Availability (SA), the artificial degradation of the broadcast satellite clocks. This argument in favor of the GLONASS is no longer valid because SA has been deactivated for the GPS as of May 2, 2000.

At present there are two geodetic type receivers available on the market tracking GPS and GLONASS satellites simultaneously on both frequencies, the Ashtech Z18 receiver and the TPS (Topcon Positioning Systems) Legacy receiver.

Unlike the GPS the GLONASS uses Frequency Division Multiple Access (FDMA) technology to discriminate the signals at the antenna, whereas the signals of the GPS satellites are distinguished by different modulated codes (Code Division Multiple Access, CDMA). All GLONASS satellites transmit the same C/A- and P-codes, but each satellite has slightly different carrier frequencies.

The nominal carrier frequencies for the L1 and L2 signals may be written as follows:

$$f^n_{(1)} = f^0_{(1)} + n \cdot \Delta f_{(1)} \tag{2.5a}$$

$$f^n_{(2)} = f^0_{(2)} + n \cdot \Delta f_{(2)} \tag{2.5b}$$

where

n $\ldots$ $n = 1, \ldots, 24$: frequency channel number,
$f^0_{(1)}$ $\ldots$ 1602 MHz, L1 frequency for a GLONASS satellite with channel number 0,
$\Delta f_{(1)}$ $\ldots$ 0.5625 MHz, frequency increment on L1 for two subsequent channel numbers,
$f^0_{(2)}$ $\ldots$ 1246 MHz, L2 frequency for GLONASS satellite with channel number 0,
$\Delta f_{(2)}$ $\ldots$ 0.4375 MHz, frequency increment on L2 for two subsequent channel numbers.

The frequency ratio $f^n_{(2)}/f^n_{(1)}$ is constant for all GLONASS satellites and amounts to $7/9$. Because some of the GLONASS frequencies interfere with frequencies used for radio-astronomy the following changes in the frequency plan are expected [*ICD*, 1998]:

- **1998-2005:** The GLONASS satellites will only use frequency channel numbers n = 0,...,13. The channel numbers 0 and 13 may be used for technical purposes. Antipodal satellites may use the same channel number.
- **Beyond 2005:** The GLONASS satellites will switch to frequency channels n = -7,...,$+6$, where the channel numbers $+5$ and $+6$ are only used for technical purposes. Antipodal satellites may use the same channel number. In addition, the satellites launched beyond 2005 will use filters limiting their out-of-band emissions.

The actual frequency channel numbers are broadcast in the navigation messages.

The GLONASS Navigation Message

The entire navigation message is contained in so-called superframes, which have a duration of 2.5 minutes. Each superframe consists of five frames with a duration of 30 seconds. Each of these frames contains the immediate data (data of the transmitting satellite) plus the non-immediate data (almanac information of 5 satellites in case of frames 1–4, almanac information of 4 satellites in case of frame 5). In this way the almanac information of the entire GLONASS system (nominally consisting of 24 satellites) is broadcast within one superframe, whereas the immediate data is repeated 5 times within each superframe.

The immediate data comprise

- the time tag corresponding to the beginning of the frame,
- the time to which the broadcast ephemerides refer,
- the health flag for the transmitting satellite,
- the difference between the satellite's clock reading and GLONASS system time,

- the (predicted) difference between the satellite's carrier frequency and its nominal value,
- the ephemerides of the satellite,
- the age of the ephemerides data.

In contrast to the GPS, where the broadcast ephemerides are defined by modified Keplerian elements, the broadcast ephemerides of the GLONASS satellites are defined by positions and velocities referred to an Earth-centered and Earth-fixed system (PZ-90). In addition, the accelerations of the satellites caused by the Sun and the Moon is given in the same system. Normally, the broadcast ephemerides of the GLONASS satellites are updated every 30 minutes.

The non-immediate data comprise

- information on the health status of all GLONASS satellites,
- the orbital parameters of all GLONASS satellites within the space segment (almanac data),
- the frequency channel numbers of all GLONASS satellites,
- the correction of GLONASS system time with respect to UTC(SU).

For more details we refer to [*ICD*, 1998].

2.4.3 IGEX and IGLOS: Global GLONASS Campaigns

In 1998 the first global GLONASS observation campaign (International Glonass EXperiment, IGEX) was organized by the International Association of Geodesy (IAG), the International GPS Service (IGS), the Institute of Navigation (ION), and the International Earth Rotation Service (IERS). The main objectives of the campaign were to

- test and develop GLONASS post-processing software,
- determine precise GLONASS orbits in a well defined Earth-fixed reference frame,
- determine transformation parameters between the terrestrial reference frame PZ-90 (used for the GLONASS) and the ITRF (used by IGS for the GPS),
- investigate the system time difference between the GLONASS and the GPS, and
- collaborate with the SLR (Satellite Laser Ranging) community to evaluate the accuracy of the computed GLONASS orbits.

CODE took part in the campaign as an analysis center processing measurement data of the IGEX observation network shown in Figure 2.6. The following products were generated for GPS weeks 990–1066: precise GLONASS orbits, system time differences between the GLONASS and the GPS, transformation parameters between PZ-90 and ITRF 97 [*Ineichen et al.*, 1999]. Furthermore, the impact of combined processing of the IGS and the IGEX network and the modeling of the radiation pressure parameters for GLONASS satellites were studied [*Ineichen et al.*, 2000].

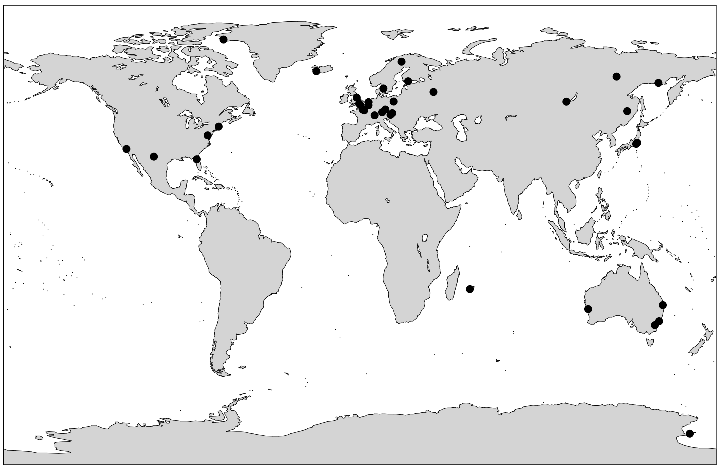


Figure 2.6: The IGEX observation network as used by the CODE analysis center.

All GLONASS satellites are equipped with a LASER retro-reflector array. The SLR ground network tracked nine satellites during the IGEX campaign. These SLR measurements enabled a totally independent check of CODE's improved GLONASS orbits and proved them to have an accuracy better than 20 cm. Figure 2.7 shows such a comparison of the GLONASS broadcast orbits and the improved CODE orbits with SLR measurements over a period of about half a year.

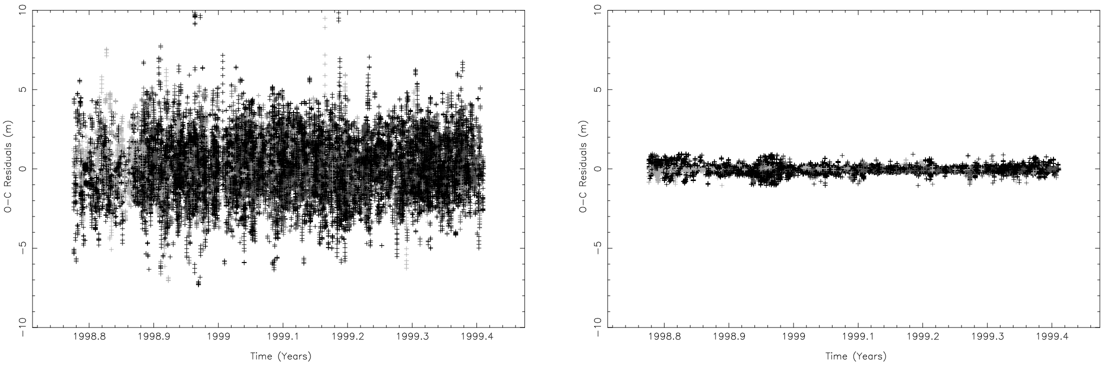


Figure 2.7: Comparison of broadcast GLONASS orbits (left) and CODE precise orbits (right) with SLR measurements.

The IGS Governing Board has approved the continuation of the IGEX campaign within the scope of an IGS GLONASS Working Group. The main tasks of this International GLONASS Service Pilot Project (IGLOS-PP) consists of the establishment and maintenance of a global GLONASS tracking network, and the computation of precise orbits, satellite clock estimates, and station coordinates. Furthermore, the impact of GLONASS on atmospheric products and estimated Earth rotation parameters will be studied.

The inclusion of the GLONASS into the *Bernese GPS Software* provided us with experience in using two different satellite navigation systems simultaneously. Different satellite signals, different reference frames, and different time scales are the major issues in this context. The gained experience is especially valuable in view of new upcoming satellite systems, like the proposed European GALILEO system. The know-how of processing combined GPS and GLONASS data will facilitate the inclusion of GALILEO and possibly other new satellite systems into the *Bernese GPS Software*.