FURTHER DEVELOPMENT OF THE GPS AND OF GPS RECEIVERS

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Abstract

The GPS (Global Positioning System) is now becoming the operational system. Analysis of the system in the test phase has resulted in the development of different receiver types, which will be discussed. A prospect for further developments is given and the suitability for the operational phase is discussed.

Introduction

The GPS has become a well known navigation system with a wide civil user community and broad civil applications. The GPS will provide information that can be used to improve land transportation, mapping, air traffic, search and rescue operations and space operations.

Defined as the primary military navigation system for the next decades by the Department of Defence (DoD) and the guaranteed civil usage without fees, has caused a high interest and a dynamic development of various civil receivers.

A lot of tests were carried out showing the high capabilty and accuracy of the GPS. With the change to the operational phase and the launching of Block II space vehicles the testing phase will be replaced by the operational phase. The questions for further improvements and for artificial degradation for civil users will be of main interest. This will have an effect on the development of civil receivers and also on the attraction of GPS. Thus, other systems like LOCSTAR, a regional civil system which also comprises communication facilities, may become more and more attractive.

GPS Navigation

GPS is a passive system and operates through triangulation to four satellites, providing accurate 3D position in WGS84, velocity and time. For civil application the Standard Positioning Service (SPS) and for military and other authorized users the Precise Positioning Service (PPS) is available. The PPS provides 3D accuracy of 16 m SEP (spherical error probable), while the SPS will be degraded to 100 m 2dRMS (2 dimensional rms) by artificial Selective Availability (SA) errors on the GPS signal.

The GPS is divided into three segments:

- the Space Segment is made up by the satellites themselves
- the Control Segment comprises the monitor stations and maintenance facilities
- the User Segment includes the receivers that pick up the satellite signals for navigation

The **Space Segment** will consist of 18 satellites with 3 active spares in six 12h orbital planes at an altitude of 20183 km. Each satellite will continuously broadcast the navigation signals at two frequencies (L1 = 1575.42 MHz and L2 = 1227.6 MHz).

The **Control Segment** includes five monitor stations, a Master Control Station (MCS) and three ground antennas. The monitor stations are only tracking and gathering data which are transferred to the MCS. The MCS processes this information and generates ephemeries and clock bias predictions, to be uploaded twice a day to each satellite, using generally the ground antennas.

The **User Segment** consists of receivers, well designed for a particular user's needs. For navigation purposes a minimum of 4 satellites must be tracked by the receiver.

GPS - NAVSTAR Status

The development of the GPS resulting from a demand of the DoD to have a unique worldwide operable navigation system, started in 1973. In 1978 when the first NAVSTAR (Navigation Satellite for Time and Ranging) satellites were launched, an extensive test period started. In the following years the satellites listed in table 1 were launched. Currently a satellite configuration of 9 satellites can be used.

All these satellites now available exept satellite numbers 14, 13 and 16 which were launched this year, are Block I satellites, defined to be the space segment

Sat	PRN#	Launch Date	On board clock	Status (Aug. 1989)	Remarks
01	04	22.02.1978		not operational	
02	07	13.05.1978		not operational	
03	06	06.10.1978	Rubidium standard	operational	clock problems
04	08	10.12.1978	Crystal oscillator	operational	power supply problems
05	05	09.02.1980		not operational	attitude control failed
06	09	26.04.1980	Rubidium standard	operational	
07		09.02.1981			unsuccessful launch
08	11	14.07.1983	Cesium standard	operational	
09	13	13.06.1984	Cesium standard	operational	
10	12	08.09.1984	Cesium standard	operational	
11	03	09.10.1985	Rubidium standard	operational	

Table 1 Block I Satellite Launch Dates and Status

during the test phase. These Block I satellites show a continuous performance upgrade due to their on board clock. The operational satellite 4 is equipped with a quartz clocks, satellites 3,6,11 are already supplied with rubidium clocks and satellites 8,9,12 with caesium clocks.

Due to the pseudo range measurement a clock of a long term stability of 10^{-10} will cause a range measurement error of 1200m within 12 hours. This also demonstrates the sensivity to time errors in a navigation system using one way pseudo range measurements. Thus an improvement by a factor of 1000 was gained, upgrading the clocks on board of the satellites from quartz with a stability of 10^{-10} to caesium with 10^{-13}. At least a stability of 10^{-13} would be required to achieve an accuracy of better than 3m/day.

Table 2 shows the launch schedule of Block II satellites. Assuming no further delays a global 2D coverage will be available in 1990 and a full 3D operation in 1991. During an interim time a mix up of Block I and Block II satellites will be used. Due to the fact that the GPS primarily is a military system the Block II space vehicles have been designed to include a high degree of survivability and autonomy, thus radiation hardened redundant on board subsystems, active spares and certain limited on board control capability were applied. The number of on board clocks was increased to 2 rubidium and 2 caesium clocks for each satellite.

Sat	PRN#	Launch Date	Sat	PRN#	Launch Date
14	14	14.02.1989	28		04.1991
13	02	10.06.1989	29		06.1991
16	16	18.08.1989	30		08.1991
17		09.1989	31		10.1991
18		11.1989	32		01.1992
19		1990	33		04.1992
20		1990	34		07.1992
21		1990	35		10.1992
15		1990	36		01.1993
22		1990	37		04.1993
23		1990	38		07.1993
24		1990	39		01.1994
25		1990	40		07.1994
26		01.1991			
27		03.1991			

Table 2 Launch Schedule of Block II Satellites

The reduction from the early 24 satellite constellation to 18 satellites with 3 active spares has caused a degradation in the continuous redundant coverage and a severe increase of PDOPs larger than 6 for short times, in the regions marked in figure 1.

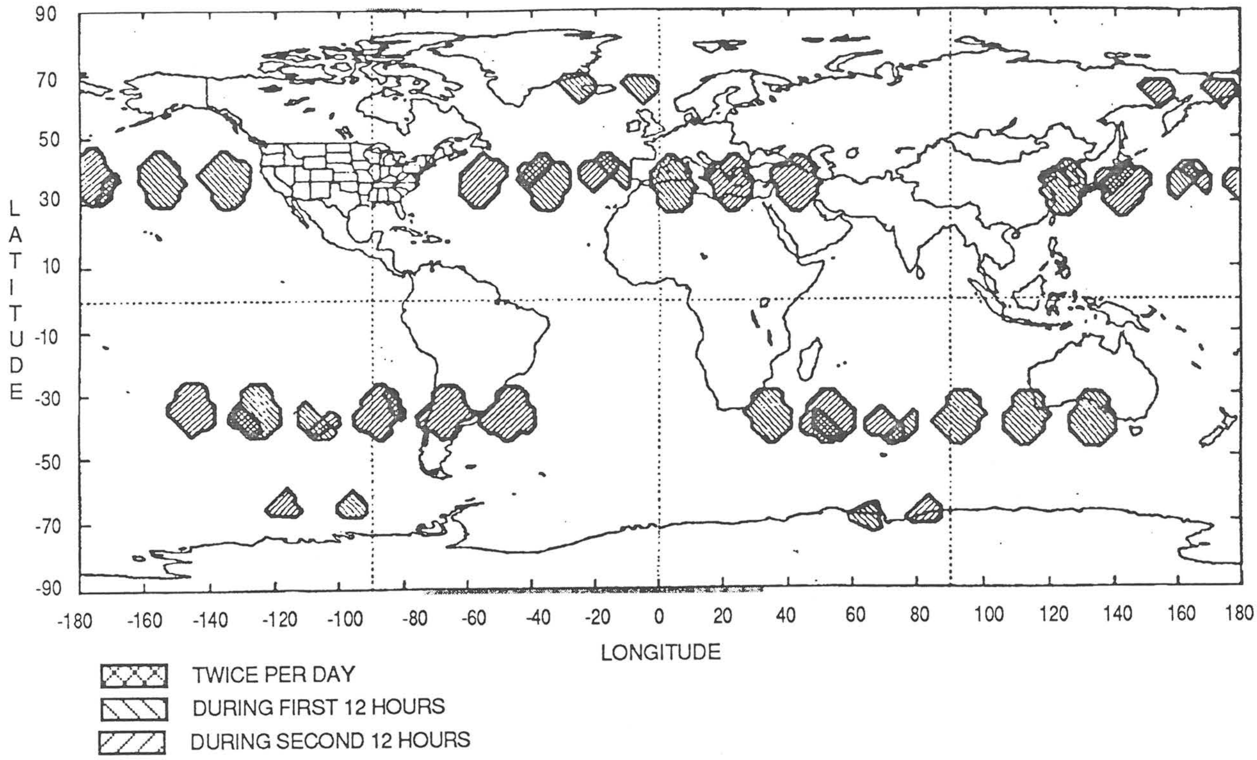

Figure 1: Zones of degraded coverage (4 satellites / PDOP > 6)

Autonomy

The satellites radiate two spread spectrum PRN signals modulated with on board clock and ephemeries information to enable for accurate navigation. This navigation message must be stored in the space vehicles memory. Autonomy now becomes important regarding the control segment will not be able to upload new navigation messages to a space vehicle. Currently a period of 14 days is stored on board of the satellites (Block II space vehicles 1 - 10). Satellites numbers 11 through 28 (Block IIA) are designed to perform for a period of 180 days without ground contact. The degradation to a normal 8 hour upload with an operational specification of 6m User Range Error (URE 1σ) will increase to 200m URE for a 14 day period and about 5km for 180 days. This will certainly lead to large absolute position errors, however with relative measurements the errors may be kept small.

A further step to autonomy is planned with Block IIR (R stands for replacement) space vehicles. Competition is underway to purchase 20 IIR satellites. Besides autonomy, survivability and improved navigation accuracy are other goals to be achieved with these satellites. These space vehicles are planned to replace failed Block II and IIA satellites with first launch in 1995.

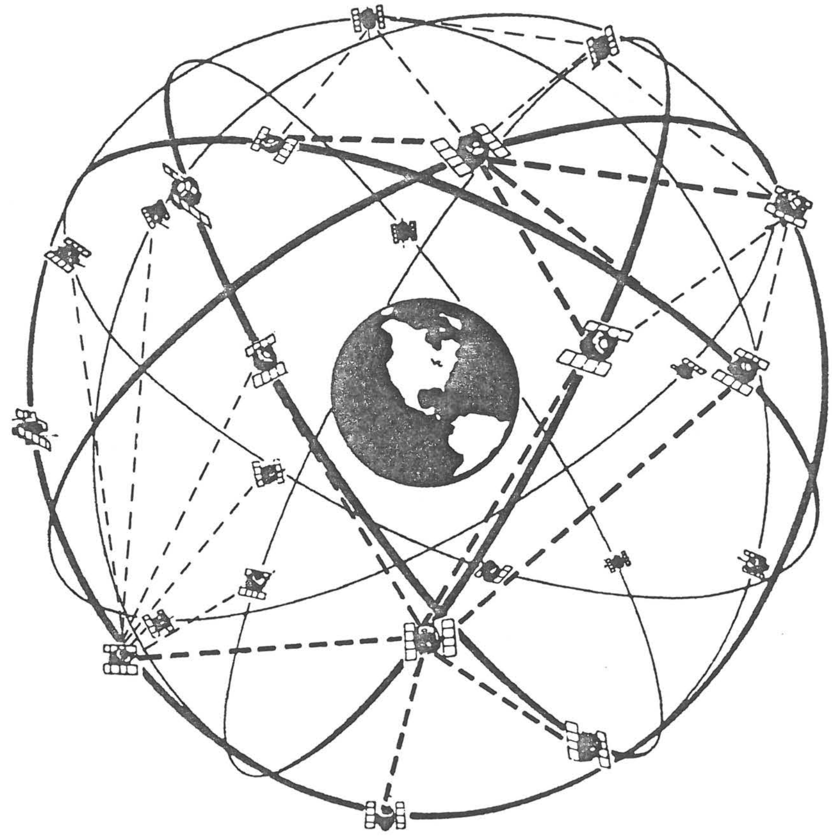

Figure 2: Block IIR satellite configuration with crosslink capability

The Block IIR satellites will also provide crosslink measurements to each other and exchange data via a crosslink communication system (Figure 2). These crosslink measurements will establish a measurement net, providing high accurate satellite positions. The great advantage is the absence of almost any atmospheric delay errors, thus improving the accuracy of range measurement between the satellites. Linking these accurate satellite positions to WGS84, using monitor stations, will provide high accurate satellite orbits, with errors less than 1 m (10 cm). The accuracy of the ephemeries is presently estimated to be at the 20-200 m level (broadcast ephemeries). For baseline estimation over 10 km, an orbit error of about 20 m will result in 10 cm baseline error.

Integrity Monitoring

The objective of integrity monitoring techniques is to ensure the accuracy and reliability of a navigation system, this means the ability of a system to provide timely warnings to users when the system should not be used for navigation purposes due to system failure, system changes or as quite often practiced now, system tests and maintenance facilities. Potential user like civil aviation depend on fast response time about satellite status.

In the current GPS configuration a failure warning response time within 90 min is guaranteed by the GPS Operational Control Segment (OCS). This delay is not acceptable for civil air navigation requirements. While GPS is a military system extensive self checking and warning features are provided to meet military integrity requirements. This self checking procedure demands for redundant satellite configuration with more than 4 satellites that can be tracked at the same time, thus a unhealthy satellite can be detected, but in degraded areas this will not be possibly all the time.

Independent integrity monitoring will need monitoring stations and a broadcast segment on one hand and a more expensive receiver on the other. The communication link of the Block IIR space vehicles will allow for faster monitoring of satellite failure.

Also the continuity of the GPS service will contribute to the acceptance of the system. This will demand for redundant signal coverage so that a single failure of one satellite will not cause interruption of the service. This requirement is not met by the constellation of 18 satellites and 3 active spares, that for short times only provides a four satellite coverage in disadvantaged regions. The probability of having all 21 satellites operational is only about 75 percent, while the probability of at least 18 satellites being operational is about 98 percent.

The deficiency of GPS coverage in our region can be reduced by looking for further aid on to the GPS. One possibilty we find in the combination with other navigation instruments like INS. Another solution can be seen in the combination of GPS with GLONASS. There is already an agreement between USA and USSR within the ICAO to provide a navigation system with 42 space vehicles and additional 6 spares. This would be a highly redundant system, but questions of systems coordination, comparable accury, information handling, receiver complexity and costs and the political dependency seems to hinder such a solution.

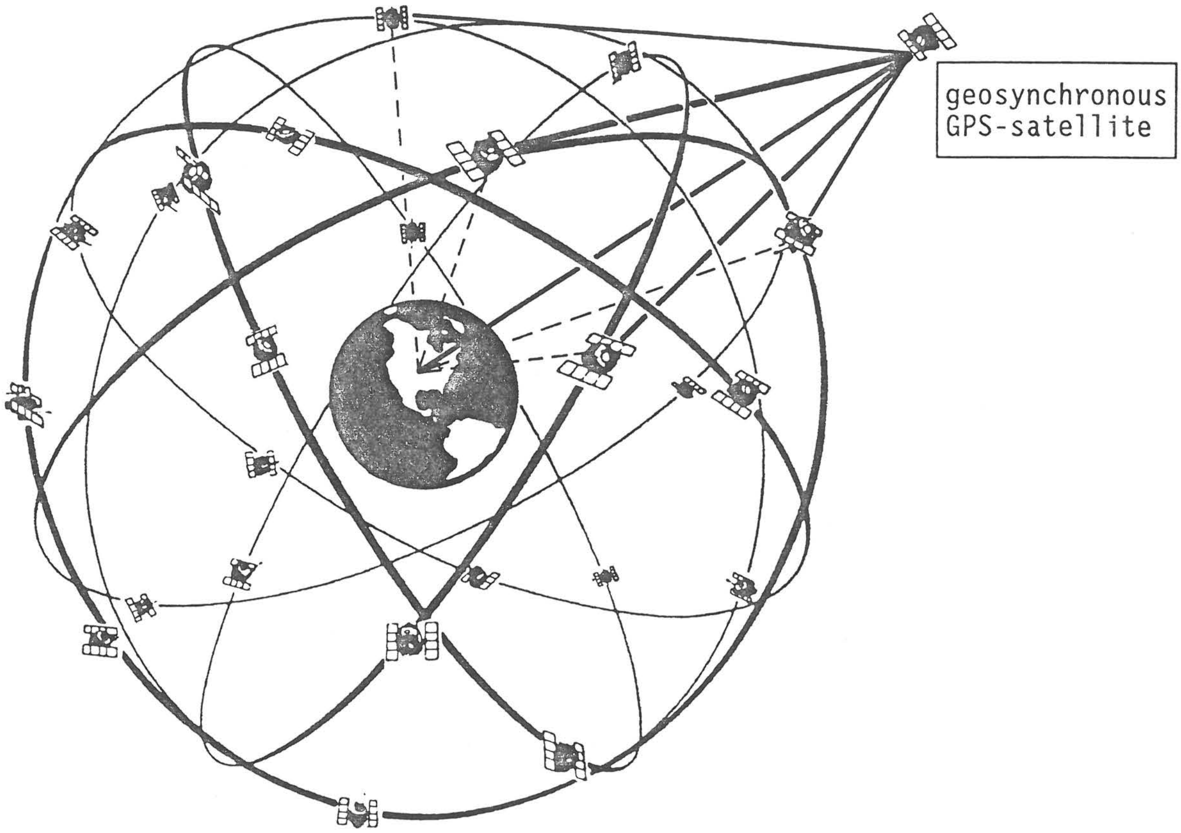

Figure 3: GPS configuration with a geosynchronous GPS satellite

The usage of a GPS satellite in a geosynchronous orbit (figure 3) - already proposed by S.Starker, DLR in 1984 - provides a possibility not only to upgrade the coverage of regions in a disadvantage but also to install communication for GPS users and allow for shorter warnings due to satellite failures, thus increasing system integrity. One handicap must be seen in the limitation that the signal of geostationary satellite cannot be received beyond 80 degree lattitude.

GPS Receiver

Corresponding to the requirements for a navigation receiver to track four satellites, a receiver must be designed to solve this task. There are basically three different receiver types of GPS receiver

- sequential tracking receivers
- multiplex receivers
- parallel continuous tracking receivers.

The **sequential receiver** tracks one satellite at a time using one or two hardware channels and combines the measurement when all four pseudo-ranges have been measured. Sequential receiver cannot operate under high dynamics but they are the cheapest solution.

A **multiplex receiver** also has only one hardware channel which switches at a fast rate (e.g. 5 msec) between the satellites being tracked, continuously collecting data for the signal processing unit. Code generator and carrier synthesizer are also time shared. Interchannel errors are eliminated because only one hardware channel is used, but signal to noise ratio is less than that of a continuous receiver.

Continuous receivers have at least four hardware channels to track 4 satellites simultaneously. Up to 12 channel receivers are available today. These receivers are the most expensive and complex receivers, but show the best performance. They can be used for high dynamics and short acquisition times (Time To First Fix) and are able to maintain accuracy under high dynamics.

In Table 3 a list of currently available GPS receiver is given.

In figure 4 a GPS receiver is shown in a Block Diagram. This block diagram stands for code correlating digital receivers that require for knowledge of the C/A-code and P-code, but there are also codeless receivers. They do not require the knowledge of the GPS codes and thus cannot read the broadcast navigaton message. This information must be supplied by an extra service and then connected to the measurements. The advantage is that they can use both frequencies and therefore compensate for ionospheric delay. These receivers are highly specialized and designed for high accurate surveying applications.

In figure 4 four main portions can be defined that meet the different tasks of a navigation receiver. The front end where the L1 and L2 signals were picked up, band limited, preselected and amplified by a low noise amplifier is an analog design, today. Down conversion with fixed translation frequencies in the IF stage produces a down-converted signal that then will be digitized through sampling for further digital processing. The digital signal processing functions include correlation, code and carrier acquisition and tracking, and data recovery. The receiver control and data processing is mostly realized by a micro

	ASHTECH			ASTROLABE	COLLINS	JMR	MINI-MAC			MOTOROLA	
	S-XII	L-XII	LT-XII	III	NAVCORE I	SATTRAK	1616	1816	2816(AT)	EAGLE	EAGLE VIII
Number of channels	12	12	12	1	1	1	6	8	8	4	8
Used GPS-frequency	L1,L2	L1,L2	L1,L2	L1	L1	L1	L1	L1	L1,L2	L1	L1
Used code	C/A	C/A	C/A	C/A	C/A	C/A	C/A	C/A	C/A	C/A	C/A
Integrated Carrier-Phase	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes
Kinematic surveys	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Photogrammetry camera input option	No	Yes	Yes	-	-	-	No	No	No	No	No
External frequency input option	No	Yes	Yes	-	-	-	No	No	No	No	No

	MOTOROLA	SEL	SNR-8	SERCEL			TRIMBLE		WILD-MAGNAVOX	
	GOLDEN EAGLE	GLOBOS	ROGUE	TR5S	NR52	NRT1	4000ST	4000SLD	WM101	WM102
Number of channels	4	6	8	5	5	3	8,12	5,10	4	7+1
Used GPS-frequency	L1	L1	L1,L2	L1	L1	L1	L1,L2	L1,L2	L2	L1,L2
Used code	C/A	C/A	C/A,P	C/A	C/A	C/A	C/A	C/A	C/A	C/A,P
Integrated Carrier-Phase	Yes	No	Yes	Yes	Yes	Yes	Yes	-	Yes	Yes
Kinematic surveys	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Photogrammetry camera input option	No	No	No	No	No	No	No	No	No	No
External frequency input option	No	No	Yes	No	No	No	No	No	No	Yes

Table 3 General view on available GPS-receivers

processor. The processor selects the best satellite configuration, combines the data and the measurements to information about position, velocity and time.

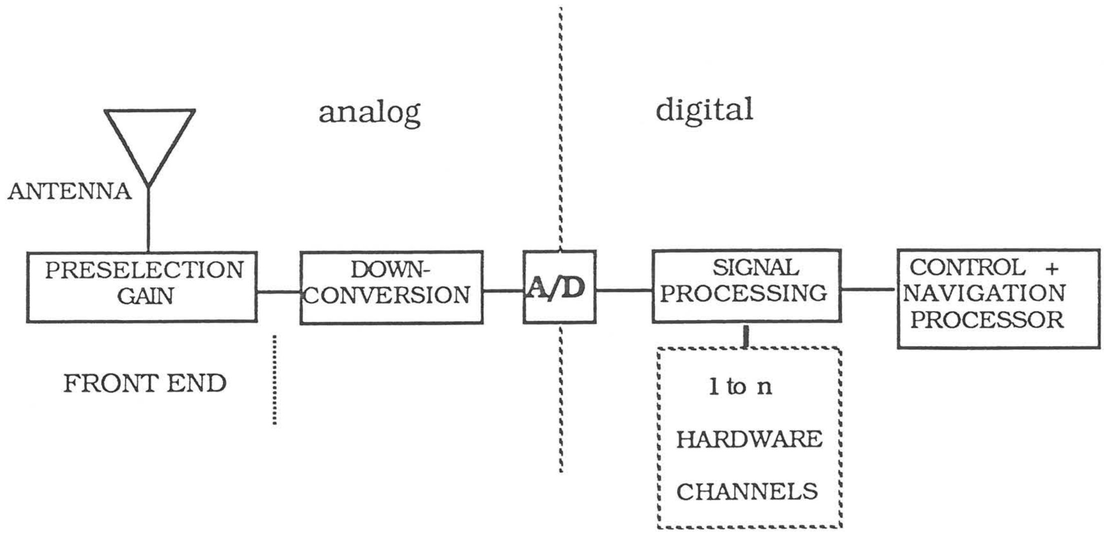

Figure 4: Block diagram of digital GPS receiver architecture

In figure 4 can be seen that the main difference between sequential, multiplexing and parallel continuous receivers can be located at the signal processing block. Since the received GPS signal remains code division multiplexed throughout front end and down conversion, this part -including A/Dof the receiver is suitable for all receiver types and for any number of satellites. This architecture for a digital receiver provides a great reduction in complexity with regard to an analog receiver and in production costs for test, calibration and maintenance.

Trends for Future GPS Receiver

Most of the digital receivers already have high density gate arrays and application specific integrated circuits (ASIC). The costs of these components will decrease with higher quantities and will be available as standard components. This will push the influence towards further digitization of receivers.
In digital receivers we always find an essential analog portion. Application of high speed digital GaAs technologies can remove various stages of analog filtering and mixing thus reducing production costs and improving receiver stability. In figure 4 the down conversion block will be eliminated and the A/D conversion takes place directly after preselection and amplification in the front end.

Conclusion

The GPS satellites in the operational phase will provide higher on board redundancy allowing for more survivability and autonomy, requested by military users. The use of two rubidium and two caesium clocks on board emphasizes the importance of high accurate time for navigation purposes. All these improvements tend to higher system performance but Selective Availability errors in the C/A-code will decrease the accuracy for civil users to about 100 m 2drms.

Future receivers will be equipped with 6 and more real channels using high integrated digital circuits. The A/D conversion will be shifted towards the front end corresponding to the availability of high speed digital (GaAs) components, producing an almost complete digital GPS receiver where only the antenna (with a low noise amplifier) will remain analog.

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Die weitere Entwicklung des GPS-Systems und der GPS-Empfänger

Zusammenfassung

Das GPS-System befindet sich zur Zeit im Aufbau zum operationellen System. Analysen des bisherigen Systems in der Testphase haben zu unterschiedlichen Empfängerentwicklungen geführt, von denen einige vorgestellt werden, und es wird ein Ausblick auf die weiteren Entwicklungsmöglichkeiten gegeben. Ihre Eignung für die operationelle Phase wird beschrieben.

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