Radio-amateur applications of GPS/GLONASS satellites

Matjaz Vidmar, YT3MV

1. Introduction to GPS/GLONASS

It is generally belived that radio-amateur applications of professional electronic systems are becoming increasingly more difficult. This is partially due also to the introduction of sophisticated digital technology, resulting in quickly changing system specifications. These systems usually become quickly obsolete and are abandoned before amateurs can make any reasonable use of them: the various MAC television transmission standards are a good example!

Things are changing slower with space-related professional systems due to the very high costs involved and longer time schedules. In particular, radio amateurs have succesfully built weather-satellite image reception equipment for all known weather satellites and all known image transmission standards.

One of the most expensive and complex professional electronic systems are satellite navigation systems. There are mainly two such systems currently being built up: the American Global Positioning System (GPS) and the Russian GLObal NAvigation Satellite System (GLONASS). Both are intended to replace a variety of ground-based radio-navigation aids and as a side product, to provide any suitably equipped user with very accurate time (100ns) and very accurate frequency (10^-12).

Both systems have been in developement for more than 10 years and they are promised to be operated for at least the following 15 years, with compatible satellites to follow afterwards. Other organizations, such as Inmarsat, also intend to broadcast similar radio-navigation signals from their satellites.

Since satellite radio-navigation signals are available and are promised to be available in the future in the same, unchanged data format, to any suitably equipped user free of charge, I think that we radio-amateurs should at least look at the possibility to use these signals for our own purposes as well. The system specifications are known and are published [1], [2] and [3].

The principle of operation of the GPS or GLONASS navigation system is the following: the satellites broadcast very accurate timing signals. A completely passive user (receive-only) measures the time delays on the signals and computes the distances to the satellites. If enough satellites are available in different positions on the sky, the user can compute his three-dimensional position from distance measurements. In practice the user must receive four satellites at the same time to solve for four unknowns: his three coordinates and accurate time. Similarly, from Doppler shift measurements on four satellites the user can compute all three components of his velocity vector and accurate frequency.

In practice there are several natural and technical limitations when building a navigation satellite system. For example, many satellites are required for a system with continuous global coverage 24 hours per day. Higher orbits allow a full coverage with less satellites, but they are more influenced by gravitational effects from other celestial bodies, especially the Sun and the Moon. Both GPS and GLONASS satellites are in similar orbits: GPS satellites are in 20000km high circular orbits with a period of about 12 hours and GLONASS satellites are in 19000km high circular orbits with a period of about 11 hours and 15 minutes. The orbits have an inclination to the equatorial plane of between 55 degrees (GPS) and 65 degrees (GLONASS) to ensure a good distribution of the satellites across the sky for users anywhere on the Earth surface.

The RF carrier - operating frequency choice is also subjected to different limitations. For navigation purposes, higher frequencies allow wider modulation spectra for more accurate timing measurements and less propagation disturbances, but require higher power transmitters on the satellites as well, since the users are supposed to use omnidirectional receiving antennas. Both GPS and GLONASS use the L-band frequency range between 1.2 and 1.7GHz. The satellites transmit on two different RF channels to allow for ionospheric propagation corrections: all GPS satellites transmit on two frequencies L1=1575.42MHz and L2=1227.6MHz, different satellites are separated by code-division multiplexing. GLONASS satellites use the more conventional frequency-division multiplexing on 25 equally spaced L1 channels between 1602 and 1615.5MHz and 25 L2 channels between 1246 and 1256.5MHz.

The block diagram of the equipment onboard a GPS or GLONASS satellite is shown on Fig. 1. The accurate frequencies and timing signals are obtained from an onboard atomic frequency standard through a frequency synthesizer. Current satellites use cesium-beam frequency standards. The RF carriers are modulated with known codes, called P (Precision) and C/A (Coarse/Acquisition). Accurate timing measurements are obtained so that the receiver tries to match the transmitted code with a locally generated replica. The modulation of the RF carrier is straightforward PSK (0/180) obtained with balanced modulators.

The GPS/GLONASS signals also contain navigation data, transmitted at 50bps. The navigation data is simply exclusive-or-ed to the C/A and P codes before modulation. Of course the navigation data needs to be encoded because of the constraints of the RF channel, including many error-checking parity bits, and formatted into frames for synchronization recovery.

The navigation data essentially includes the orbital parameters of the satellite. Using these parameters the accurate position of the satellite can be computed at any time. The navigation message further includes the corrections for the onboard satellite clock, since it is much easier to broadcast a few corection coefficients than readjusting a complicated atomic clock in space. Finally, the navigation data also includes the system almanac: an abridged set of orbital and clock parameters with reduced accuracy for all of the satellites in the system (planned 24 for each system, currently 18 GPS and 11 GLONASS operational satellites).

2. GPS/GLONASS receiver design

Both GPS and GLONASS are primarily intended as military systems. This practically means that they may not be available to their full accuracy to civilian users and in particular, the P code transmission may not be available to unauthorized users. In practice most of the users, including radio-amateurs, are constrained to the slightly less accurate C/A code.

Therefore, only the design of a simple, single channel C/A-code receiver will be discussed here. All cheap commercial GPS receivers are simple single-channel C/A units, and similar receivers were also developed, built and tested by the author. Of course some design parameters, like the gain distribution or the conversion frequencies used, are only provided as an example referred to the authors' prototypes and may be changed.

The block diagram of a single-channel GPS receiver is shown on Fig. 2. The GPS C/A code has a length of 1023 bits and a repetition period of 1ms, which results in a bit rate of 1.023Mbps and a RF bandwidth of roughly 2MHz. The omnidirectional quadrifilar helix antenna captures the signals from all visible GPS satellites transmitting at 1575.42MHz. The 2MHz wide frequency band is first amplified and then downconverted to a suitable IF frequency for further processing. In the prototype GPS receiver, the first IF is centered around 102MHz and the second IF is centered around 10MHz.

Before deciding about further signal processing or selecting the demodulator the signal-to-noise ratio should be evaluated first. In the wideband IF the signal-to-noise ratio is very poor: the signal level is usually between -20dB and -10dB below the noise level, represented not only by the random thermal noise, but mainly by the signals from other visible GPS satellites, which transmit on the same RF channel and cannot be separated by the omnidirectional antenna.

This very low signal-to-noise ratio is very common in all spread-spectrum receivers, where the signal-to-noise ratio is improved after the correlation with the locally-generated code: the bandwidth of the desired signal is shrinked by several orders of magnitude while the bandwidth of the thermal noise and other unwanted signals is expanded, the final result being a much improved signal-to-noise ratio in the now much narrower bandwidth of interest.

In the case of GPS, the bandwidth of the desired signal is shrinked from 2MHz to less than 100Hz (50bps navigation data modulation) while the thermal noise and other signals are expanded to a bandwidth of roughly 4MHz. The overall signal-to-noise ratio is therefore improved by 46dB, bringing the desired signal well above the noise level.

Since the signal-to-noise ratio is very low before the correlation with the locally generated code, the overall signal-to-noise ratio is not much affected by signal limiting or other distortions. Hard-limiting only brings a signal-to-noise degradation of about 2dB and therefore a limiting IF amplifier is used in all simple GPS receiver designs.

Although an all-analog spread-spectrum code correlator and synchronizer and 50bps PSK navigation data demodulator can be built, these circuits are complicated and bulky. It is much more simple to use digital signal processing, especially since the limited wideband IF signal can be represented by 1 bit quantization without any loss in the signal-to-noise ratio!

The design of a GLONASS receiver is similar to a GPS receiver except for the required frequency agility, since GLONASS satellites transmit on different RF channels. The block diagram of a single-channel GLONASS C/A receiver is shown on Fig. 3. The GLONASS C/A code has a length of 511 bits and a repetition period of 1ms, resulting in a bit rate of 511kbps and a RF bandwidth of roughly 1MHz.

Since different RF channels are by GLONASS, the noise is only represented by the thermal noise and the resulting RF signal-to-noise ratio is better than with GPS: the signal level is only between -10dB and 0dB below the noise level in the wideband IF.

There are however other constraints in a GLONASS receiver. First, the signal modulation delay variation has to be kept small when switching between channels, since time differences between different satellite signals are actually what is to be measured by the navigation receiver to find the user position! Therefore, channel selection has to be performed in front of narrow filters with unknown group-delay variations and is best done in the first downconversion step.

Second, the switching between different RF channels has to be performed in a short time, less than 1ms, if the single-channel receiver is to be time multiplexed among four different satellites required for the navigation solution. Finally, the frequency synthesizer phase noise should be low enough to allow 50bps PSK data demodulation (about 20dB better than the requirements for a SSB transceiver frequency synthesizer). All these requirements result in a PLL synthesizer with a loop downconverter and a comparison frequency equal to the channel spacing of 562.5kHz.

The block diagram of the dedicated DSP hardware is shown on Fig. 4. The DSP hardware is much simplified since the limited wideband IF may be sampled to just 1 bit accuracy with no signal-to-noise ratio degradation. Frequency mixing or signal multiplication can be performed by simple exclusive-or gates and counters with clock enables can be used as accumulators or integrators.

In order to maintain the mathematical correlation properties of the codes used, the integration period has to be set to an integer multiple of the code period, which is equal to 1ms for both GPS and GLONASS. On the other hand, the sampling frequencies should be kept larger than twice the wideband IF signal bandwidth and chosen so that spectrum aliasing is avoided. Although the same samplig frequency could be used for both GPS and GLONASS, in practice it was easier to use 6139kHz for GPS and 4500kHz for GLONASS. This signal sampling also performs another downconversion to a final IF of about 2.3MHz for GPS and about 1.7MHz for GLONASS.

If the modulation code phase and the carrier signal phase were accurately known, only a single multiplier (ex-or gate) and a single accumulator (counter) would be required. This quantities are however to be measured by the receiver, which has to acquire and maintain lock on the incoming signal. Therefore, two different accumulations need to be performed for an early replica and a late replica of the satellite code to maintain code lock and both have to be further performed separately on two carriers phase shifted by 90 degrees (I and Q), since the absolute carrier phase is not known at this stage either.

The required carriers can be generated with a digital circuit called a "Numerically Controlled Oscillator" (NCO). A similar NCO can be used to supply the clock to the feedback shift-registers that supply the pseudo-random sequences that match the satellite codes. In a practical GPS or GLONASS C/A code receiver it is however easier to use a lookup table stored in a RAM, that is periodically updated by a microprocessor.

The dedicated DSP hardware produces four different accumulation sums at a relatively low rate: once per millisecond. Any further processing can be thus easily performed in software on a general-purpose 16 bit microprocessor: search for code lock, maintain code lock, acheive carrier lock and demodulate the 50 bps navigation data. To avoid having to write new lookup tables too frequently, the hardware address counter can be preset by an adjustable delay generator from the microprocessor. Of course this delay needs to be accounted for when processing the I and Q components to acheive carrier lock!

Finally, using the dedicated DSP hardware in place of analog circuits has yet another advantage. The dedicated DSP hardware can be easily time-multiplexed between different satelite signals without having to reacquire lock after switching to another satellite: the code and carrier phases can be stored in the microprocessor memory and used to predict the code and carrier phases when the same satellite signal is once again accessed in the multiplexing sequence.

In a complete receiver design, the same microprocessor is of course also used to compute the positions and velocities of the satellites and solve the navigation equations to obtain the three-diemsional user position, velocity vector and an accurate time and frequency reference.

3. Amateur use of GPS/GLONASS

The GPS and GLONASS systems are mainly intended for navigation: user position and velocity determination. The absolute position accuracy is in the range of 30m for both systems, depending of course on the signals used (P or C/A code), averaging time, receiver type (number of channels) etc.

Although the navigation itself is not of much interest to radio amateurs, it would probably make much more sense to transmit GPS or GLONASS coordinates of a contest location rather than the inaccurate EU or WW locator, which is already not accurate enough for serious microwave or laser communications. By the way, GPS and GLONASS use almost the same coordinate system and a long time average shows differences in the order of only 10m between the two systems.

A side product of both GPS and GLONASS is accurate time and frequency broadcast. In order to acheive the specified navigation accuracy, the timing measurements have to be performed to an accuracy of about 10ns. The same requirement applies to the onboard satellite atomic clocks. The final user time transfer accuracy ranges between 30ns and 100ns, depending also on the knowledge of the exact user location. Thus the user should also compute his position even if he only needs accurate time.

Radio-amateurs could use this time transfer capability of both GPS or GLONASS every time when accurate synchronization is required. Coherent communications are just an example, the accuracy of GPS or GLONASS offers more than this: for example, the actual propagation path of the radio signal and the propagation mechanism could be investigated in this way.

The frequency broadcast accuracy of both GPS and GLONASS is in the range of 10^-12, far better than can be acheived with HF or LF standard frequency transmitters. The accuracy of the latter is limited to around 10^-7 by the propagation effects alone, and this is not enough for serious microwave work. GPS and GLONASS are also available globally 24 hours per day and are not limited by the transmitter range, propagation effects or low-frequency electronic pollution.

Finally, GPS and GLONASS represent a step away from being just an operator of black-box amateur-radio equipment. Although there are several ready-made GPS receivers on the market, we will probably have to develop our own receivers for our experiments, both the hardware and the software. Building such a receiver may be an interesting challenge as well.

4. References

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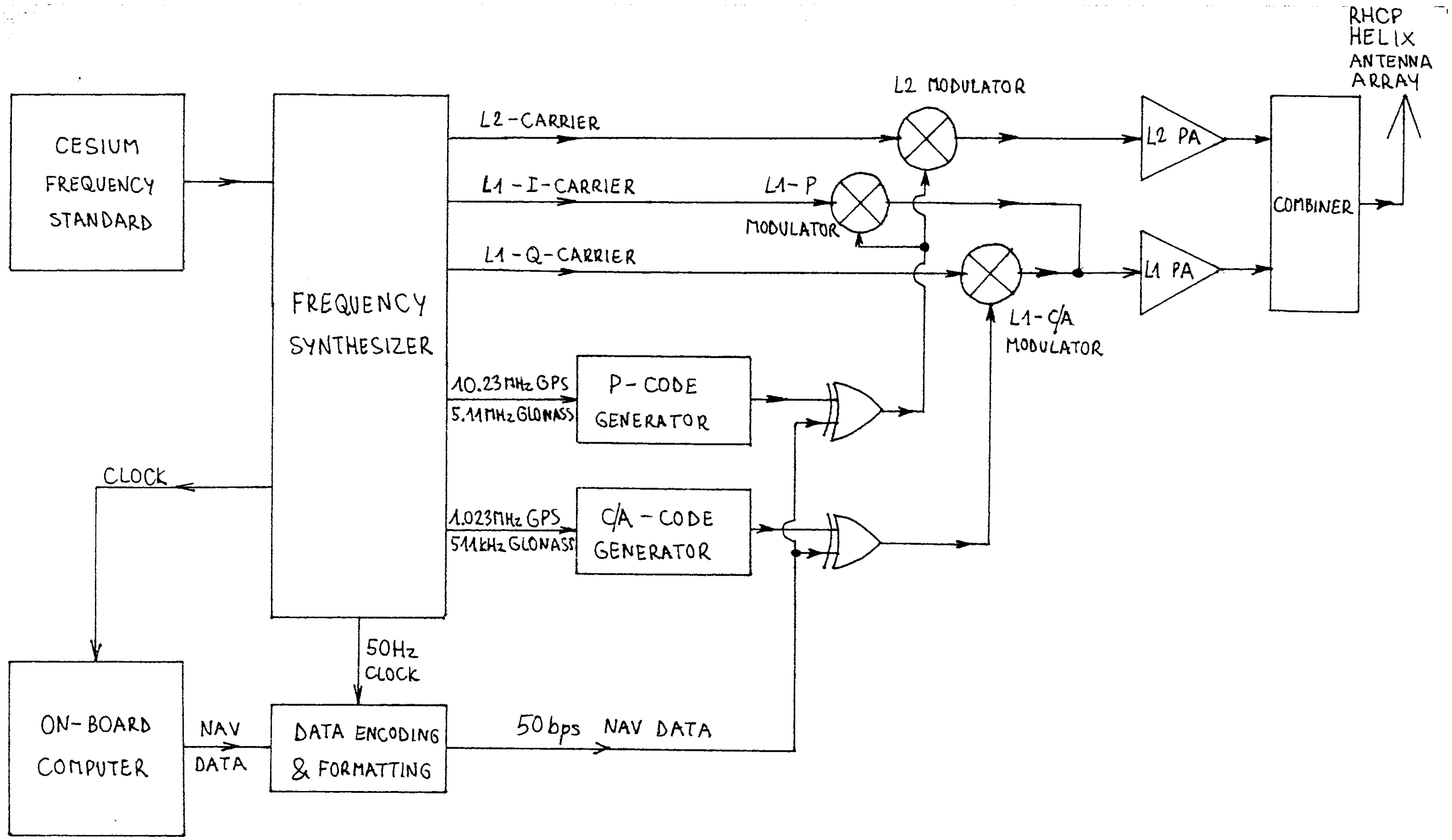

Fig. 1 - GPS/GLONASS satellite block diagram.

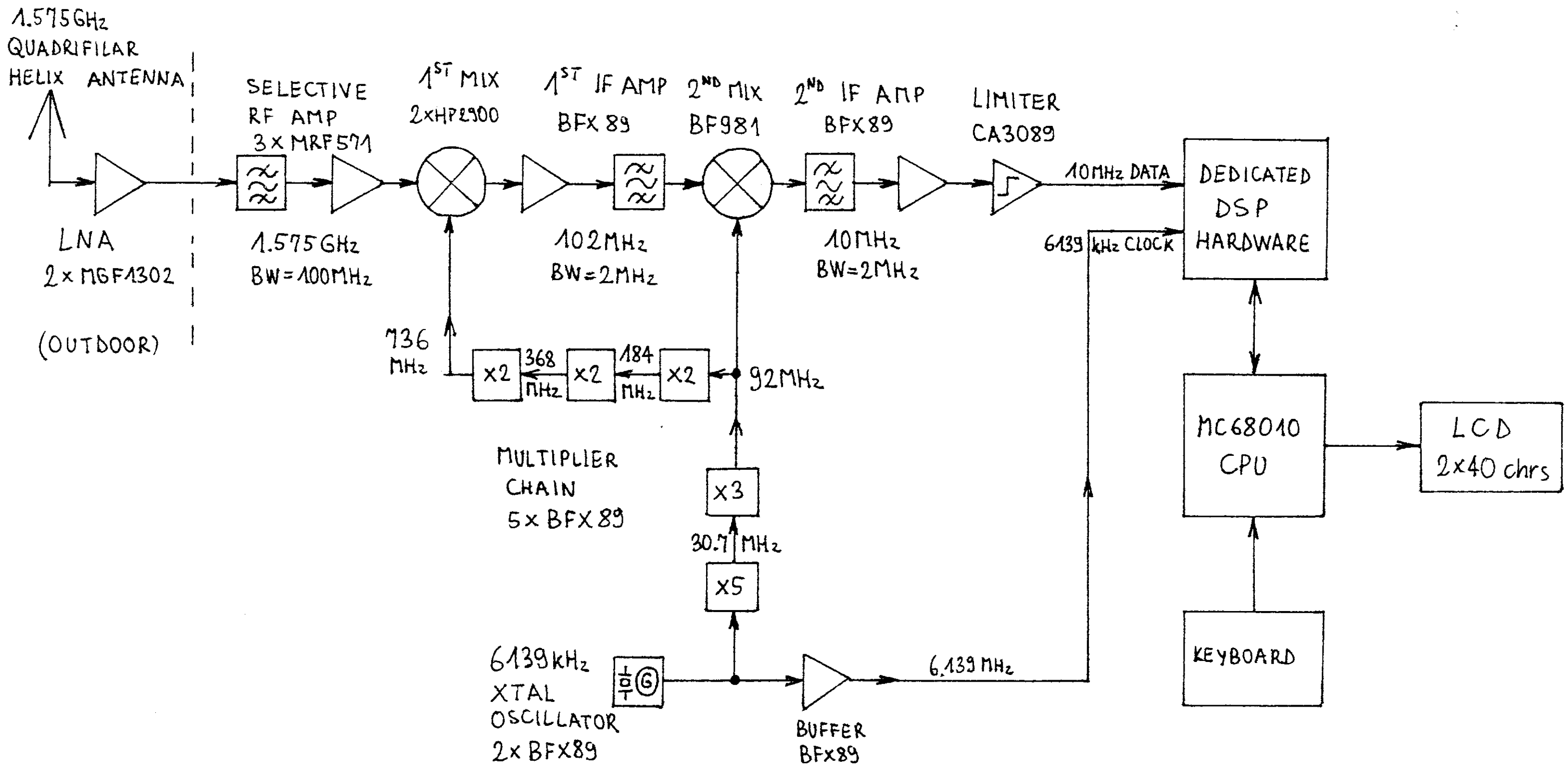

Fig. 2 - GPS receiver block diagram.

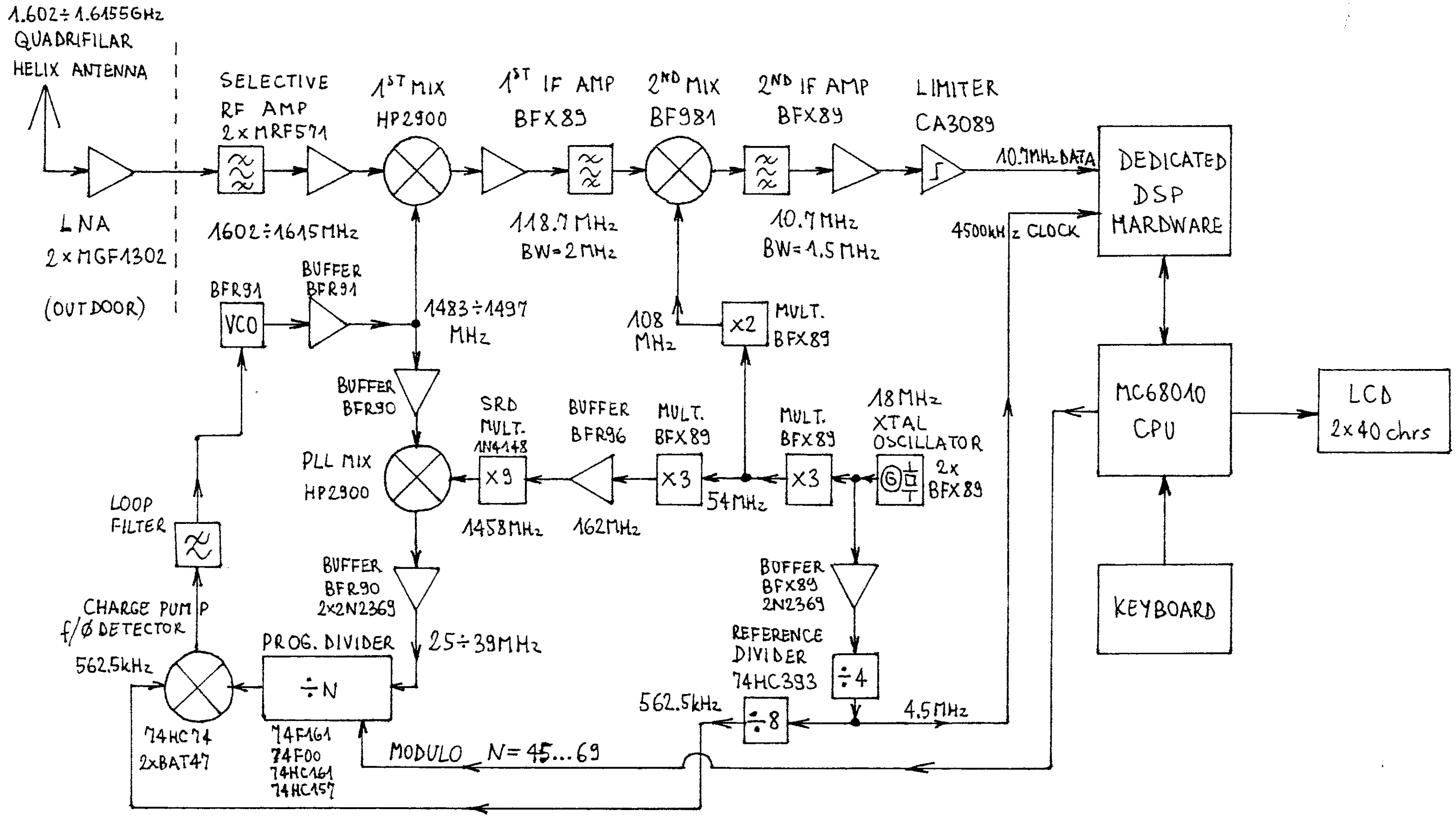

Fig. 3 - GLONASS receiver block diagram.

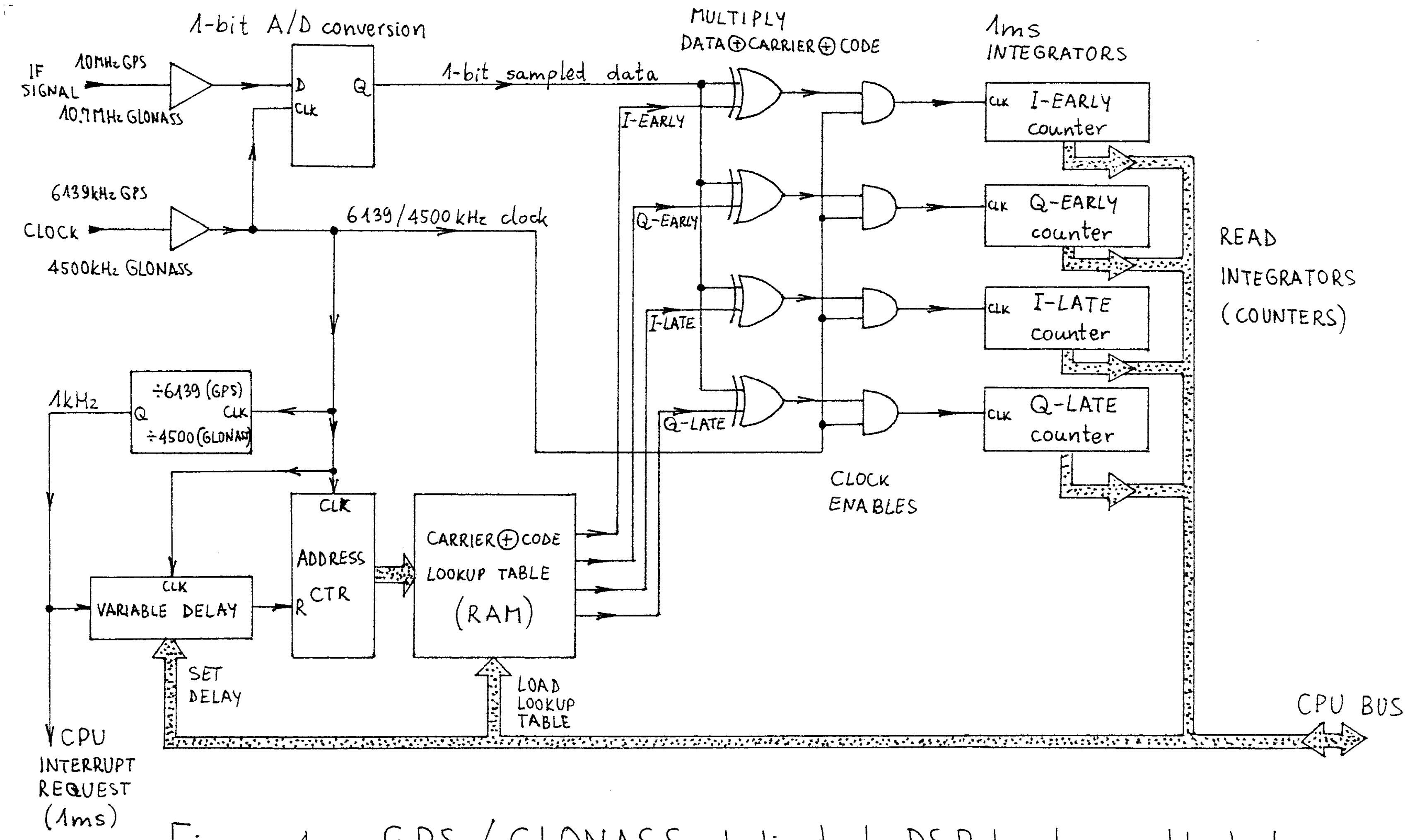

Fig. 4 - GPS / GLONASS dedicated DSP hardware block diagram.