# Performance comparison between GIOVE-A signals and GPS based on wideband measurements with the BayNavTech$^{TM}$ Signal Evaluation Facility (BaySEF$^{TM}$)

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## BIOGRAPHY

Dr. Melanie Kaindl graduated in 1998 in electrical engineering at the Aachen University of Technology. In 2005 she received her Ph.D. in communications engineering from the Munich University of Technology. Since 2005 she works at EADS Astrium specialized on satellite navigation signal performance analysis, receiver algorithms and application experiments.

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## ABSTRACT

In this paper we present evaluations of wideband GIOVE-A and GPS measurements. The data is recorded with the BayNavTech Signal Evaluation Facility (BaySEF) which is a high performance wideband and flexible GNSS receiver and signal performance evaluation platform. Measured fine resolution correlation functions are shown as well as the tracking performance of different signals depending on early-late spacing. All measurements are compared with theoretical evaluations.

## 1 INTRODUCTION

The modernization of the current GPS satellite navigation system but also the development of the Galileo[1] system led to the introduction of several new satellite navigation signals over the last years. Theoretical investigations have shown promising gains of the modern navigation signals over the current GPS-C/A. In January 2006 the first Galileo test-satellite GIOVE-A started transmitting some of the new signals, for instance BOC(1, 1) in L1 and AltBOC(15, 10) in E5. These signals are now available for performance verification under real transmission conditions which is the focus of this paper. We discuss different tracking performance aspects of measured GIOVE-A signals and compare the results with theoretical expectations and with GPS-C/A.

Measurement and processing of the various navigation signals in different frequency bands requires a high performance and flexible navigation receiver. The BayNavTech Signal Evaluation Facility (BaySEF) which is currently built up at EADS Astrium fulfills these requirements. It can be shortly characterized as a flexible wideband navigation receiver and evaluation platform for the signal performance analysis of measured satellite navigation signals, like from GIOVE, Galileo and GPS. One component of the BaySEF is an accurate offline navigation receiver which is used for post-processing of the recorded baseband samples. It realizes acquisition, tracking and the evaluation of several signal characteristics and provides many adjustable parameters. The large flexibility of the measurement system and navigation receiver enables us to cover with the BaySEF "high-end" down to "low-end" receivers.

We used the BaySEF to measure and process GIOVE-A and GPS signals. The evaluations of these measurements are presented in Section 4. Before, in Section 2 the key features of the BaySEF are introduced and subsequently in Section 3 an overview over the properties of the offline navigation processing facility is given. Conclusions are drawn in Section 5.

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[1] Galileo is a trademark of the European Commission and the space program Galileo is a joint initiative of the European Commission and the European Space Agency.

## 2 BAYNAVTECH SIGNAL EVALUATION FACILITY (BAYSEF)

We recorded navigation signals with the BaySEF which consists of two identical measurement systems and an offline processing unit as schematically shown in the block diagram in Figure 1. Each system can process up to four navigation frequency bands simultaneously selectable from E5, E5a, E5b, E6, L1 and L2. One measurement system is stationary and located at EADS Astrium in Ottobrunn near Munich. The other system can be used as stationary extension or as mobile system, e.g. for simultaneous measurements at two different locations with unequal interferer and multipath scenarios.

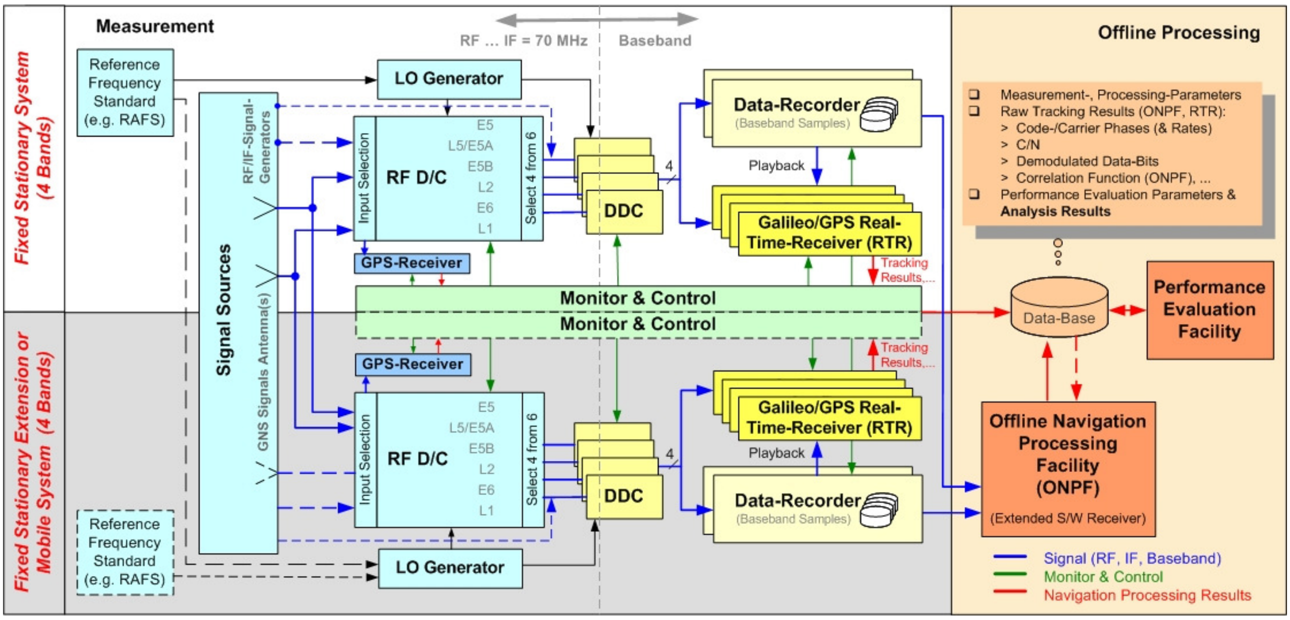


**Figure 1.** BaySEF block diagram

The BaySEF provides a selection of different signal sources. Real GNSS signals are received either with a 3m steerable parabolic dish or a wideband (950 – 1650 MHz) omni-directional antenna. Signal generators can be attached at RF and IF for all or individual frequency bands which enables performance investigations of new navigation signals as well as interference simulations. The signals can be monitored at RF and IF.

The BaySEF enables reception of the full GPS and Galileo signal spectra due to its 3dB bandwidth of more than 50 MHz in E5a, E5b, E6, L1 and L2 and more than 100 MHz in E5, respectively. In the RF front-ends the signals are down-converted in two steps to an IF of 71.61 MHz. The synchronized DDCs allow an input bandwidth of 400 kHz to 150 MHz. The analog signals are sampled with a sample-rate of 460 MHz. Programmable FIR low-pass filters with adapted data rate decimation (possible decimation factors between 2 and 275) enable a bandlimitation to almost any bandwidth. The signal is digitized with adjustable quantization of 2, 4, 8 or 16 bits. A programmable complex-valued FIR-filter equalizes the BaySEF's amplitude and phase distortions.

The data recorders' large capacities allow continuous recording of at least 80 minutes per band with a recording rate of at least 120 MByte per second and band which is of importance for long-term investigations.

We apply two types of navigation receivers, an offline software receiver which is described in the succeeding section and real-time GPS/Galileo receivers which simultaneously process the individual signals during the measurement. Each real-time receiver is based on a FPGA with GNSS-Core and LEON-processor for the navigation software. It simultaneously tracks up to 12 satellites per band each with up to 5 correlators. Many processing parameters are adjustable as tracking modes, loop parameters and bandlimitations. The data can be played back with real-time rate from the data recorders to the GPS/Galileo receivers. For further details concerning the BaySEF we refer to [1].

## 3 OFFLINE NAVIGATION PROCESSING

The offline navigation processing unit consists of an offline navigation receiver, a data base and a performance evaluation facility (see Figure 1). The navigation receiver processes the recorded baseband samples and outputs navigation raw-data which is then evaluated.
The navigation receiver is a highly flexible and accurate software receiver, implemented in C. It realizes acquisition, tracking and the evaluation of several signal characteristics. The major receiver output-parameters are C/N, carrier-phase, code-phase and (de)coded navigation data bits. The tracking loops are implemented accounting for the theoretical discrete update impacts on the underlying differential equations. Except of the recorded signal that is stored as discrete values, the whole processing of the discrete-valued signal is done with pure floating point arithmetic. As one consequence for instance our software has no limitations to restrict correlator-spacings to a multiple of the sample duration. The tracking loops are to a great extend very flexible. Different discriminators, correlator spacings and various loop parameters can be chosen. Moreover, a selection of different tracking modes as BOC and AltBOC is provided. The receiver allows further bandlimitation of the navigation signal with adapted data rate reduction to enable single-sideband processing but also to adjust for high performance (large bandwidth) down to low performance receivers (small bandwidth). Some additional features are implemented as the computation of precise correlation functions with arbitrarily fine resolution. The large number of adjustable parameters but also the possibility to extend the software receiver enables investigations far beyond normal receiver operations.

Examples of these investigations are the identification of optimized tracking parameters and algorithms as well as the performance analysis of new navigation signals. We can identify and extract error sources as multipath and interference from the navigation signal by comparison with theory. Moreover, the transmission characteristics can be analyzed, e.g. of the satellite transmission. In the following, first evaluation results of BaySEF measurements are given.

## 4 EVALUATION RESULTS

We simultaneously measured signals in the L1 and E5 frequency band during GIOVE-A's visibility on January 31, 2007 at 13:10 h and also on March 5, 2007 at 10:20 h. In both cases, we used the stationary BaySEF equipment with the omni-directional wideband antenna located on the roof of the EADS Astrium building in Ottobrunn near Munich. The characteristics of the recorded signals are listed in Table 1. Some details concerning the characteristics of the GPS and GIOVE-A signals that are considered in this paper are given in Table 2.

| Frequency Band | Sample Rate [MHz] | 3 dB Bandwidth [MHz] | Quantization [bit] |
|---|---|---|---|
| L1 | 57.5 | 46 | 4 |
| E5 | 115 | 92 | 4 |

**Table 1.** Characteristics of recorded signals

| | GIOVE-A | | | GPS |
|---|---|---|---|---|
| | L1-A | L1-B | E5a-Q | C/A |
| Modulation | BOCc(15, 2.5) | BOC(1, 1) | BPSK(10)* | BPSK(1) |
| Carrier Frequency [MHz] | 1575.42 | 1575.42 | 1176.45 | 1575.42 |
| Data / Pilot | Data | Data | Pilot | Data |
| Primary Code Length [ms] | 10 | 4 | 1 | 1 |
| Chip Rate [MHz] | 2.5575 | 1.023 | 10.23 | 1.023 |

**Table 2.** General characteristics of GIOVE-A and GPS signals.
* Note that E5a is a single-sideband of the AltBOC(15, 10) signal in E5.

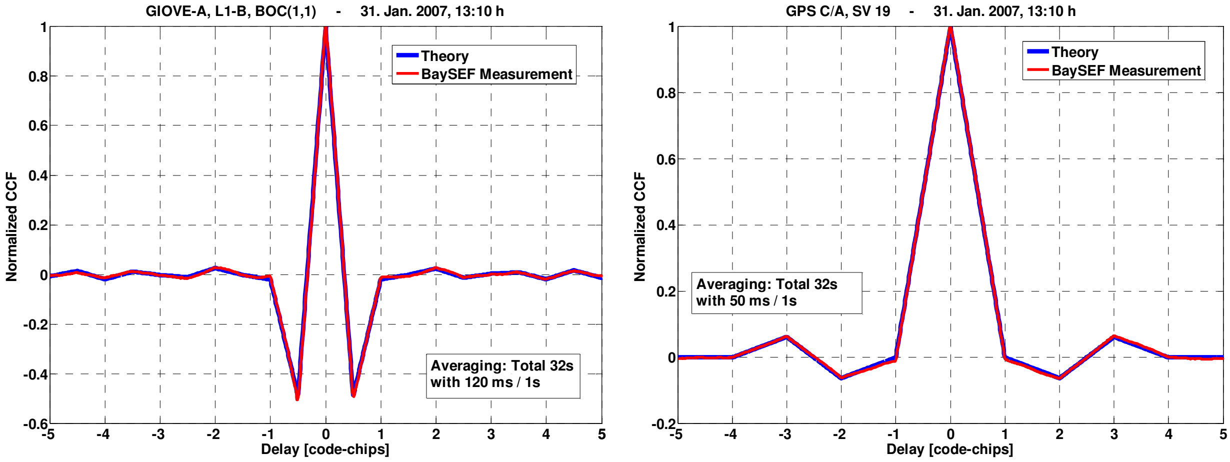
### 4.1 Measured Correlation Functions

We computed cross-correlation functions (CCFs) between the incoming and the reference signal with the offline navigation receiver. Examples of the real part of these functions are presented in Figures 2 and 3 for different navigation signals in comparison with theory. The correlation functions were determined intermediately whilst tracking with very fine resolution of more than twice the sampling rate (> 100 MHz). To reduce noise, the functions were coherently averaged over a total duration of 32 s.

Figure 2 shows measured and theoretical correlation functions of GIOVE-A, L1-B (left-hand side) and GPS-C/A, SV 19 (right-hand side), respectively. The theoretical curves were derived under the assumption of no bandlimitation. In case of the BOC(1,1), we did not just consider the auto-correlation but also the cross-correlation between the L1-B and L1-C ranging codes. As it can be seen, measurement and theory match extremely well in both cases.

In Figure 3 correlation functions of GIOVE-A's L1-A signal are presented. The function on the left-hand sided plot represents single-sideband (SSB) processing of the BOC(15, 2.5) with a bandlimitation of 5.115 MHz. As reference signal a BPSK(2.5) was used. As before, the theoretical and measured curve fit very well. Compared to the sharp peaks of the correlation functions in Figure 2, the rounded peak shows clearly the impact of the bandlimitation.

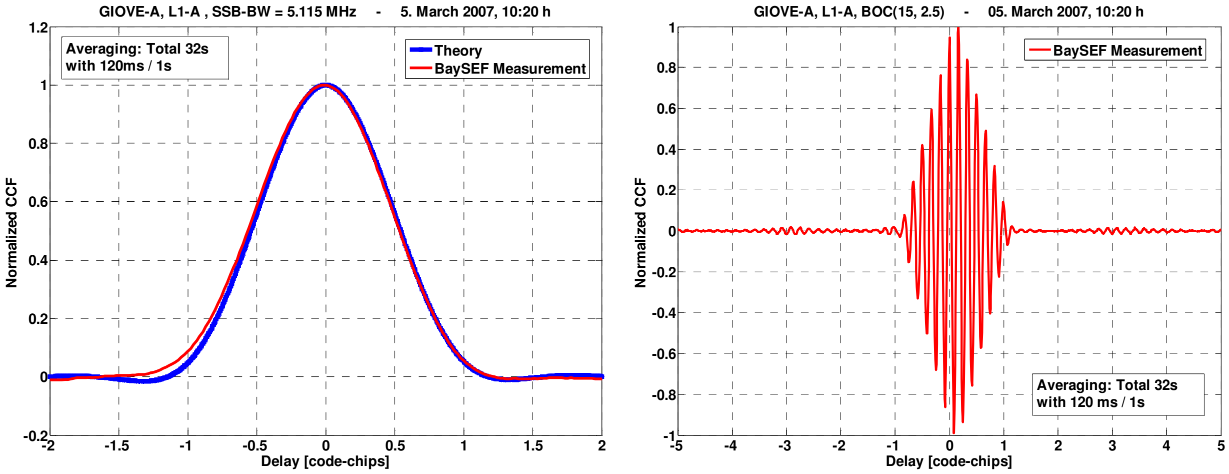
The entire BOC(15, 2.5) correlation function is depicted in the second plot of Figure 3. Comparing the right-hand with the left-hand side of the main correlation peak, an unsymmetry of the curve can be observed. We assume this effect is due to imperfections of the payload's transfer characteristics and maybe also of the BaySEF's since we did not equalize the amplitude and phase distortions of our equipment during this particular measurement. Furthermore, the correlation function is slightly shifted towards positive delays which illustrates the failure of the acquisition in finding the main correlation function peak.



GIOVE-A, L1-B, BOC(1,1) - 31. Jan. 2007, 13:10 h

GPS C/A, SV 19 - 31. Jan. 2007, 13:10 h

**Figure 2.** Measured cross-correlation functions of GIOVE-A, L1-B and GPS-C/A, SV 19



GIOVE-A, L1-A , SSB-BW = 5.115 MHz - 5. March 2007, 10:20 h

GIOVE-A, L1-A, BOC(15, 2.5) - 05. March 2007, 10:20 h

**Figure 3.** Measured cross-correlation functions of GIOVE-A, L1-A (single-sideband and dual-sideband)

## 4.2 Tracking Performance Comparison

In the following, we present the tracking performance of different measured GIOVE-A and GPS signals. The tracking performance is discussed in terms of code-jitter behavior depending on early-late spacing in comparison with theoretical evaluations and with each other. Three different theoretical curves are computed based on the derivation given in [2]. The curves differ in how the transmission characteristic is considered:

- A non-limited bandwidth is assumed.
- The transfer characteristic of the BaySEF is considered.
- The transfer characteristic of the BaySEF and an estimate of the payload's transfer characteristic are considered, where the latter is modeled by a filter of 40 MHz bandwidth.

As tracking processing parameters a loop bandwidth of 20 Hz was chosen for both the code and carrier loop. We applied a non-coherent early-late discriminator for the code loop. The coherent integration time is identical to the primary code length of the individual signals (see Table 2). The signals are not further bandlimited, i.e. the 3 dB bandwidth remains 46 MHz in L1 and 92 MHz in E5.

In Figure 4 (left-hand side) the code-jitter of GIOVE-A's L1-B signal component is shown. The measured carrier-to-noise-ratio equals 42.55 dBHz. Note that the large code-jitter values result from the chosen loop bandwidth of 20 Hz. This high loop bandwidth provides sufficiently independent samples for the code-jitter evaluations even for short processing durations which simultaneously avoid static multipath.
As can be seen in the figure, for early-late spacings larger than 0.025 code-chips the measured code-jitter degrades with increasing early-late spacings. Below this value, it behaves contrary. A comparison with the code-jitter curve for no bandlimitation shows that it generally estimates a too pessimistic tracking performance. In contrast, in the region of narrow early-late spacings the predicted code-jitter is too optimistic. A much better fit of theory and measurement is achieved, when considering the transfer characteristics. Especially for narrow early-late spacings, where the bandlimitation becomes more relevant, we can observe an excellent fit of theory and measurement if the BaySEF and an assumed payload transfer characteristic are considered.

A similar comparison is depicted in Figure 4 (right-hand side) for the E5a-Q signal of GIOVE-A. As before, the measurement and theory are almost identical for small early-late spacings (below 0.1 code-chips). For larger early-late spacings both curves still fit very well.

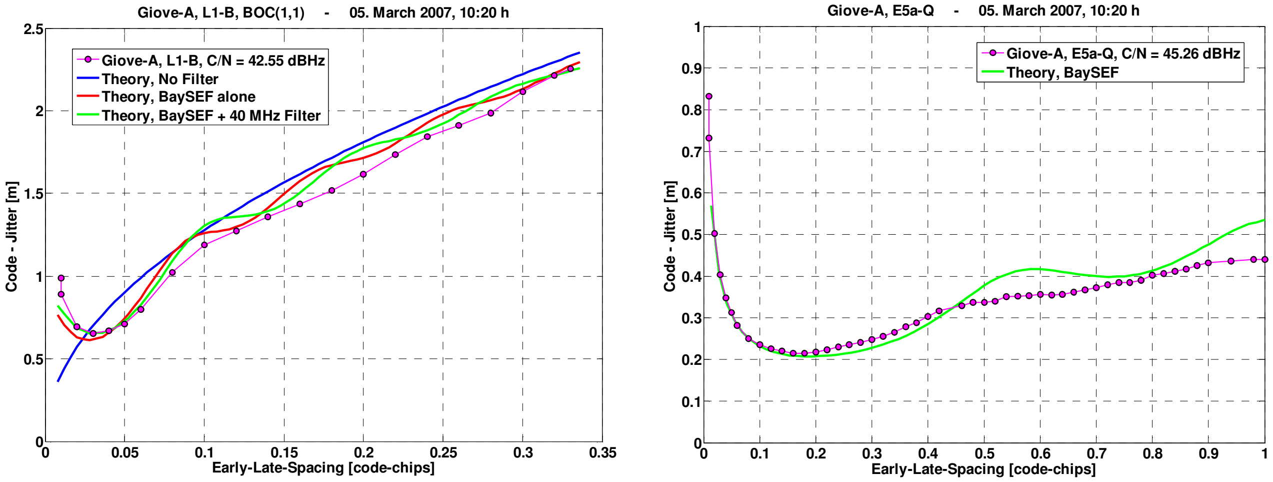


**Figure 4.** Measured code-jitter compared with different theoretical evaluations, non-coherent early-late discriminator
Left: GIOVE-A, L1-B, BOC(1,1), 4 ms coherent integration time, 20 Hz loop bandwidth
Right: GIOVE-A, E5a-Q, 1 ms coherent integration time, 20 Hz loop bandwidth

In contrast to these results for GIOVE-A we observe a different behavior for GPS. Figure 5 (left-hand side) shows code-jitter curves of two different GPS satellites (SV 16 and SV 19) with a measured carrier-to-noise-ratio of 52.4 dBHz and 47.5 dBHz, respectively. As before for GIOVE-A the measured and theoretical curves fit very well for early-late spacings of less than 0.2 code-chips. Above this value, the measured code-jitter degrades much faster than the theory. We assume this is due to narrow band interference around the carrier frequency which affects GPS but not the different GIOVE-A signals and maybe also due to interference from other visible GPS satellites. Currently ongoing investigations using methodologies presented in [3], [4] and [5] have shown that these types of interference cause in fact similar tracking performance degradations.

The tracking performance of the BOC(15, 2.5) of GIOVE-A (L1-A signal) is presented in Figure 5 (right-hand side). As before, the measured and theoretical code-jitter curves are almost identical. Note that for an early-late spacing below 0.08 code-chips the same correlation peak is used for the early and late correlation. Interestingly, above 0.08 code-chips where we used two separate peaks (adjacent to the main peak) of the correlation function for the early and late correlation measurement and theory still match extremely well. This shows that in contrast to common understanding larger early-late spacings are possible even for the L1-A signal.

Finally, in Figure 6 all previously discussed code-jitter curves are shown in a single plot. To allow a fair comparison, the curves are rescaled to an identical carrier-to-noise ratio of 45 dBHz and a loop bandwidth of 1 Hz. Obviously, the L1-A signal of GIOVE-A achieves the best performance. It is directly followed by the E5a-Q signal and then by the L1-B signal. The highest code-jitter and thus the lowest tracking performance are achieved by the two GPS-C/A signals.

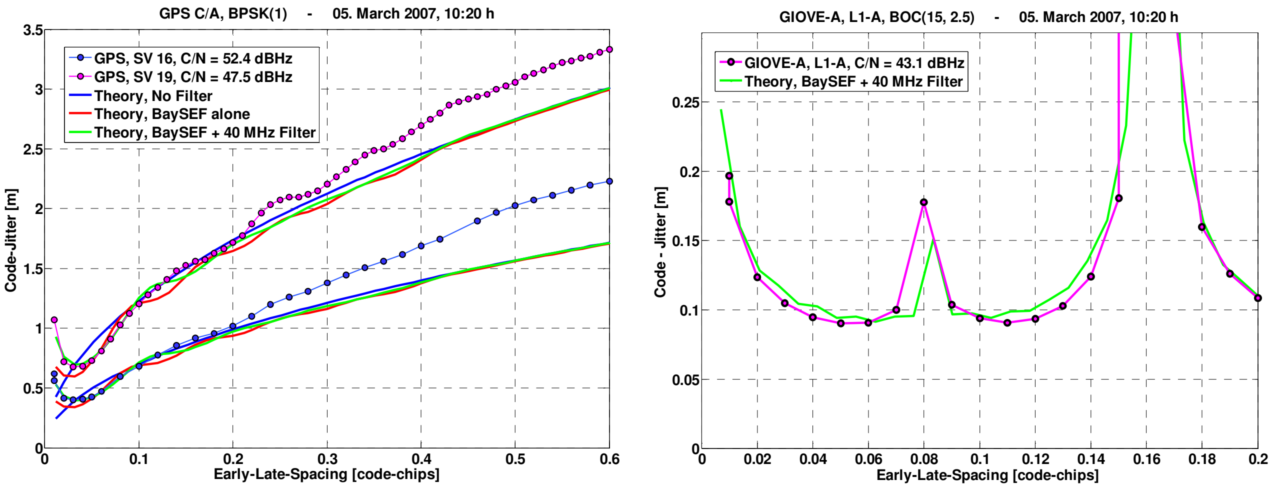


**Figure 5.** Measured code-jitter compared with different theoretical evaluations, non-coherent early-late discriminator
Left: GPS-C/A, SV 16 and SV 19, 1 ms coherent integration time, 20 Hz loop bandwidth
Right: GIOVE-A, L1-A, BOC(15, 2.5), 10 ms coherent integration time, 20 Hz loop bandwidth

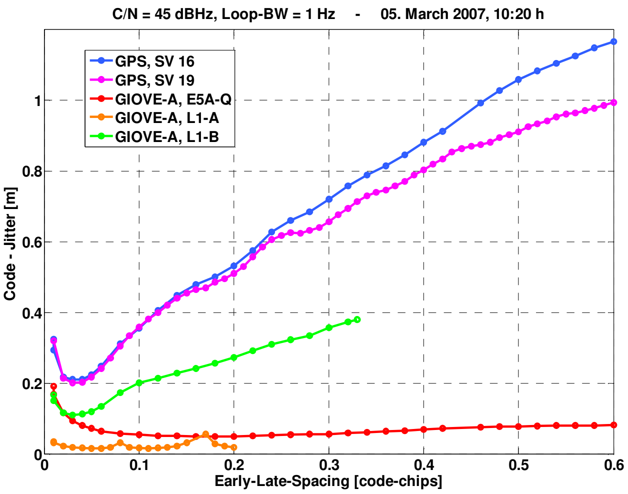


**Figure 6.** Tracking performance comparison of different GIOVE-A and GPS signals

## 5 CONCLUSIONS

In this paper we introduced the BayNavTech signal evaluation facility (BaySEF) which is a wideband GNSS receiver and signal performance evaluation platform and demonstrated its ability of successful signal sample recording. Several presented measurement evaluations of GPS-C/A and GIOVE-A signals show that the offline navigation processing unit allows initial signal processing. We presented measured correlation functions of high precision as well as tracking jitter evaluations in dependency of early-late spacing. In most cases an excellent match to theoretical evaluations can be observed.

## ACKNOWLEDGEMENT

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