

LO and Calibration Signal Distribution in a Multi-Antenna Satellite Navigation Receiver [†]

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Abstract: Due to the low signal power of global navigation satellite signals, the receivers are prone to radio frequency interference. Employing multi-antenna arrays is one method to mitigate such effects, by incorporating spatial processing techniques. The large size of the uniform rectangular arrays prevents their use in applications where installation space is limited. Therefore, we proposed a new approach, namely to split one full array into a number of smaller, spatially distributed, sub-arrays to reduce their size and exploit available installation spaces. This concept challenges the distribution of the local oscillator and calibration signals to the respective sub-arrays. This paper compares qualitatively different design concepts for a satellite navigation receiver with two two-element sub-arrays, installed multiple wavelengths apart from each other, in support of establishing an optimal choice for our intended applications in the automotive sector in terms of electrical performance and required hardware and software efforts. In general, weighing the pros and cons of the different concepts, as discussed in the paper, will assist in optimizing the system design approach for a specific application.



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Keywords: compact distributed array; GNSS receiver frontend; LO signal distribution; system calibration; satellite navigation; interference mitigation

1. Introduction

Global navigation satellite systems (GNSS) are key to safety-critical applications like automated and connected or tele-operated driving or unmanned flight maneuvering. These applications depend on the reliable availability and functionality of GNSS signaling. Due to their positioning on medium earth orbits (MEO) and the available link budgets, the respective received signal power may be as low as -130 dBm (corresponding to 10^{-16} W) at ground level [1]. This low signal strength makes the receivers prone to deliberate or unintended RF interference (RFI). Sources of unintentional distortions are, e.g., harmonic tones of local oscillators or strong signals transmitted by other wireless services in adjacent frequency bands.

Among the deliberately caused disturbances, signal jamming and spoofing attacks are of major concern [2]. The term jamming refers to the transmission of a strong RF signal in or close to the GNSS frequency bands. The signal saturates the analog frontend of the GNSS receiver, thus blocking the reception of the navigation signals. As is widely known though legally prohibited in many countries, truck drivers use so-called personal privacy devices (PPD) to hide their location from third parties [3]. Due to the low GNSS signal

power, jamming is easily achieved with an appreciable areal coverage. The detrimental impact of such jammer devices on safety-critical infrastructure or processes is frequently under-appreciated. Spoofing describes the process of deceiving a GNSS receiver, leading to false position, velocity, and time (PVT) data. Spoofing attacks are more challenging to identify, but are also more complex to implement compared to jamming.

Several methods have been proposed to achieve the immunity of a GNSS receiver against intentional or unintentional interference [4]. One possibility is to enhance the robustness of the analog receiver frontend. As an example, a receiver chain architecture able to handle lower output signal levels was less susceptible to saturation [5,6]. Another approach is the use of multi-antenna receivers in array configuration, enabling beamforming and null steering [7–9]. Dedicated digital array signal processing helps to suppress unwanted signals by directing radiation nulls towards the interfering source, or estimating the directions-of-arrival (DoA) to verify the authenticity and validity of incoming signals [10].

We previously introduced a 2×2 -element uniform rectangular array (URA) connected to a dual-frequency receiver frontend [11]. This receiver system provides both a high positioning accuracy, due to the dual-band design, and high robustness against interference, due to the array performance. Despite the compact dimensions of the array with the radiating elements separated by a quarter wavelength, these features come at the expense of a large module size of $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$. Such dimensions exceed typical installation spaces, e.g., of passenger cars, and thus prevent their penetration into a mass market. Therefore, our goal was to realize a more compact GNSS receiver system. We proposed to split the full number of four antenna elements into two distributed two-element sub-arrays [12]. This approach effectively increases the number of possible mounting spaces by enabling the installation of sub-arrays in distant parts of a car, such as side mirrors or other suitable car body appliances. A drawback of this approach, however, is the creation of grating lobes due to the electrically large element separation that challenges array signal processing like DoA estimation. This effect can be mitigated by optimizing the arrangement of the sub-arrays [13].

On the RF frontend side, the concept of spatially separated sub-arrays necessitates new concepts for the design and calibration of the receiver hardware. The local oscillator (LO) signal required for the down conversion of the received signals, as well as the calibration signal required for the precise characterization of the multiple receiver chains have to be connected to the distant sub-arrays. This paper compares different options for the distribution of the LO and calibration signals and contrasts their respective advantages and disadvantages for the example of a four-element array consisting of two identical sub-arrays mounted in the side-mirrors of a passenger car. For this installation scenario, design parameters like mechanical dimensions and the cost of the solution are the most important, along with electrical performance. If the achievable electrical performance dominates the optimization goal, the system design can lead to different conclusions.

2. GNSS Receiver with a 2×2 Antenna Array

In our dual-band 2×2 URA receiver, each patch antenna element covers the L1 band with a center frequency of $f_1 = 1575.42 \text{ MHz}$ and E5a band with $f_5 = 1176.45 \text{ MHz}$. The dual-polarized patches enable the reception of right-hand circular polarized (RHCP) as well as left-hand circular polarized (LHCP) signals [14]. A simplified block diagram of the receiver is shown in Figure 1. The antenna array provides a total number of 16 RF channels, namely $4 \times \text{RHCP}$ and $4 \times \text{LHCP}$ at f_1 and $4 \times \text{RHCP}$ and $4 \times \text{LHCP}$ at f_5 . Each channel is amplified, filtered and down-converted. The down conversion in the heterodyne receivers must preserve the magnitude and phase relationships between all received antenna signals to preserve phase coherence and thus synchronicity between the channels. A calibration signal (CAL) is provided at each channel, to determine differences in the transmission characteristics between the receiver chains. The CAL signal consists of an artificial GNSS signal which is generated in the digital baseband and up-converted to the RF domain by the LO-signal. It passes through the entire signal processing chain of each frontend channel,

is processed in the digital baseband together with the actual received GNSS signals, and is eventually compared to the initial calibration signal. This allows for a correction of gain and phase differences caused by imbalances between the channels.

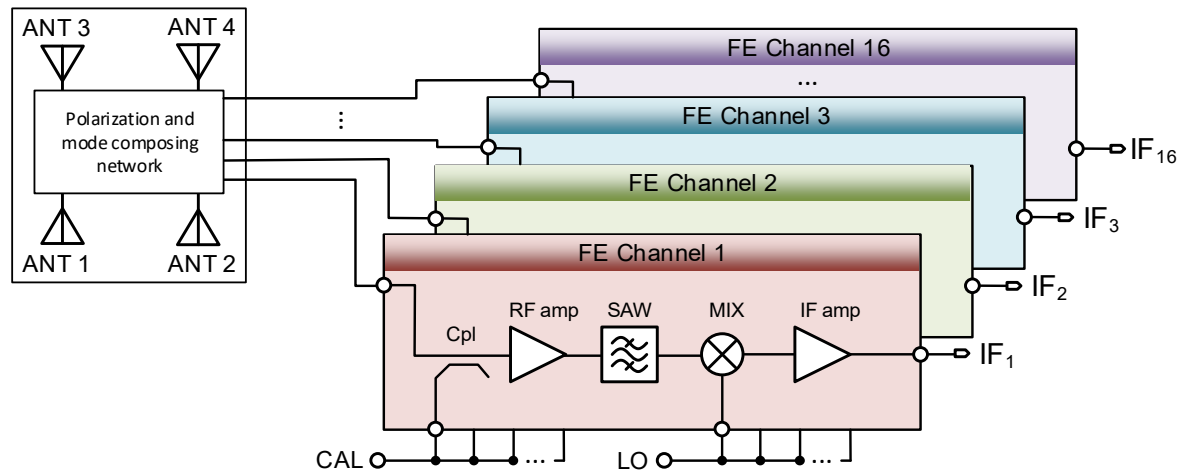


Figure 1. Simplified block diagram of the 2×2 multi-antenna dual-band dual-polarized GNSS array receiver with calibration (CAL) and local oscillator (LO) signals, leading to a total number of 16 channel outputs.

A prerequisite for the calibration algorithm is that the CAL signal be applied with identical amplitudes and phases to each receiver channel. In a compact antenna array, this condition can be met straightforwardly because all antenna elements are arranged on a common substrate; consequently, the calibration signal can be multiplexed using passive components like power splitters and distributed to the frontend channels by length-matched transmission lines. A similar conclusion holds for the distribution of the LO signal to the mixers of all receiver channels.

For the case of a distributed antenna array receiver, the above-mentioned conditions are much more challenging to meet because of the required cabling in the calibration and LO distribution paths between the two sub-arrays. As a consequence, the signals depend on the cable characteristics in terms of mechanical length differences, thermal variations and so on, leading to unforeseeable phase variations.

3. Distributed GNSS Receiver Concept with Two 2×1 Antenna Sub-Arrays

3.1. Receiver Design

Our approach of splitting one 2×2 antenna array into two sub-arrays resulted in 50% reduction of the array footprint per sub-array. Additionally, we reduced the complexity of the front-end design by processing the RHCP signals only at both frequencies, f_1 and f_5 . This led to four channels per sub-array, namely two per frequency band. A dedicated application-specific integrated circuit (ASIC) was designed for the receiver in 180 nm United Microelectronics Corporation (UMC) technology. The ASIC contains four complete receiver chains, each with two RF low-noise amplifiers (LNA), a down-converting mixer, and an IF amplifier. An external bandpass filter can be connected between the LNAs for the pre-selection of the chosen frequency band. The ASIC also contains two phase-locked loop (PLL) synthesizers to generate the LO signals at the two operational frequencies. Alternatively, external LO signals can be applied to the ASIC.

Each sub-array module incorporates one ASIC and provides four receiver channels, two for each frequency, fed by two commercially available dual-band ceramic patch antennas APAKM2507 [15], as shown in Figure 2. The complete GNSS receiver consists of two sub-arrays. The common LO and calibration signals for both frequency bands, provided by the central base-band module, have to be split and fed to the sub-arrays

by cable connections, as illustrated in Figure 3. Due to such a distributed arrangement of the two sub-arrays, the provision and distribution of identical and phase-coherent CAL and LO signals is challenging and requires dedicated considerations of the various trade-offs involved.

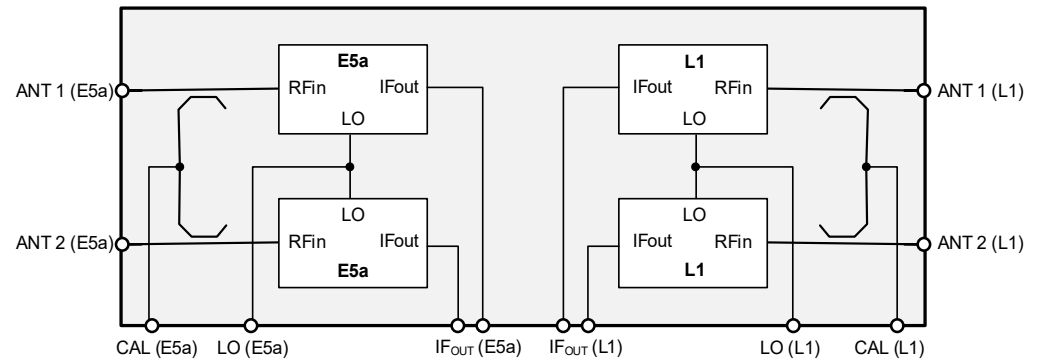


Figure 2. Principal block diagram of a dual-band sub-array of the distributed GNSS receiver. The four receiver channels are shown with their respective RF and LO inputs and IF outputs. Each sub-array contains a CAL and LO signal distribution between the two receiver chains at each frequency band.

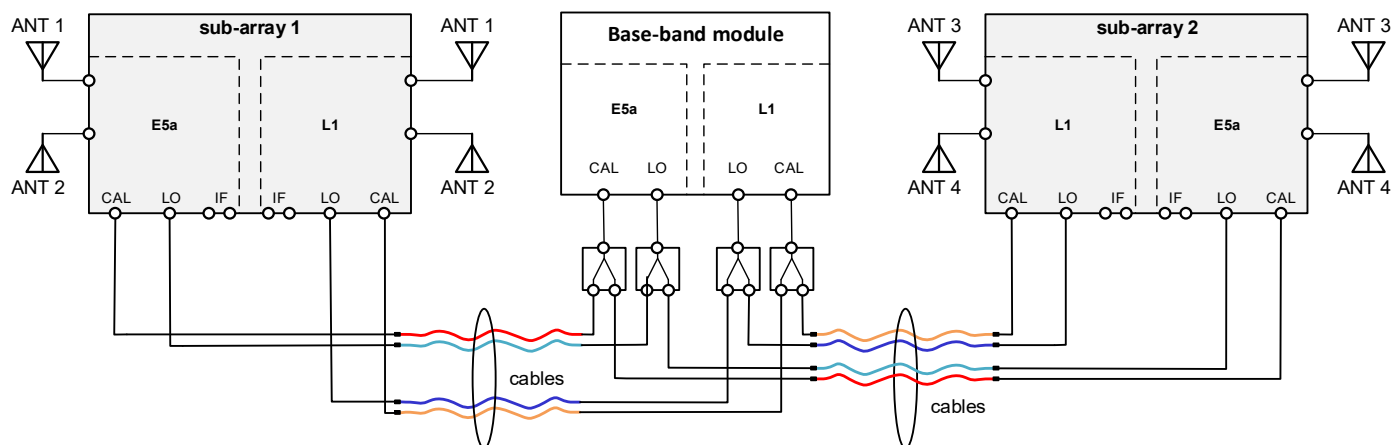


Figure 3. Block diagram of the complete GNSS receiver consisting of two sub-arrays and a central base-band module. The LO (REF) and calibration signal for both frequency bands are split and distributed to the sub-arrays by cable connections.

3.2. System Calibration

3.2.1. LO Signal Distribution

There are two options to provide the LO signal; the first and most obvious one is to generate the LO signal in a common PLL-based synthesizer using a single crystal-based reference oscillator, to split the signal in two identical signals by means of a power divider and to distribute it to both sub-arrays with low-loss coaxial cables. A second option is to distribute the reference signal (REF) instead, and employ two PLLs at each sub-array to synthesize the LO signal locally. Since both signals are derived from the same reference signal, the output signals of both PLLs remain phase-coherent.

The schematic in Figure 4. illustrates the two options. In Figure 4a, one common PLL module synthesizes the LO signal using the 10 MHz REF signal. The LO signal is split into two identical signals and distributed to the sub-arrays, where they are directly available for down-converting the input signals. In Figure 4b, a common reference signal at a frequency of $f_{\text{ref}} = 10$ MHz is split into two identical copies and distributed to the sub-arrays. Each sub-array incorporates its own PLL-based LO signal generator. In both cases, cables of significant lengths are required to feed the sub-arrays with the REF and, respectively, LO

signal. The phase coherence required for the array signal processing is challenged by mechanical and thermal tolerances and variations, as well as other environmental effects. As one example, one side of the car can be subject to sunshine, the other side being shaded. The resulting temperature differences may lead to significant changes in the electrical length. The thermal phase sensitivity depends strongly on the type of cable. For teflon-insulated coaxial cables, maximum phase changes above 2500 ppm were reported [16]. For such a cable of 2 m length, as used in our study, this would result in phase changes of up to 17.5° at the LO frequency of 1648 MHz, causing errors in the DoA estimation algorithms. Phase-stable cables would come at the expense of increased costs.

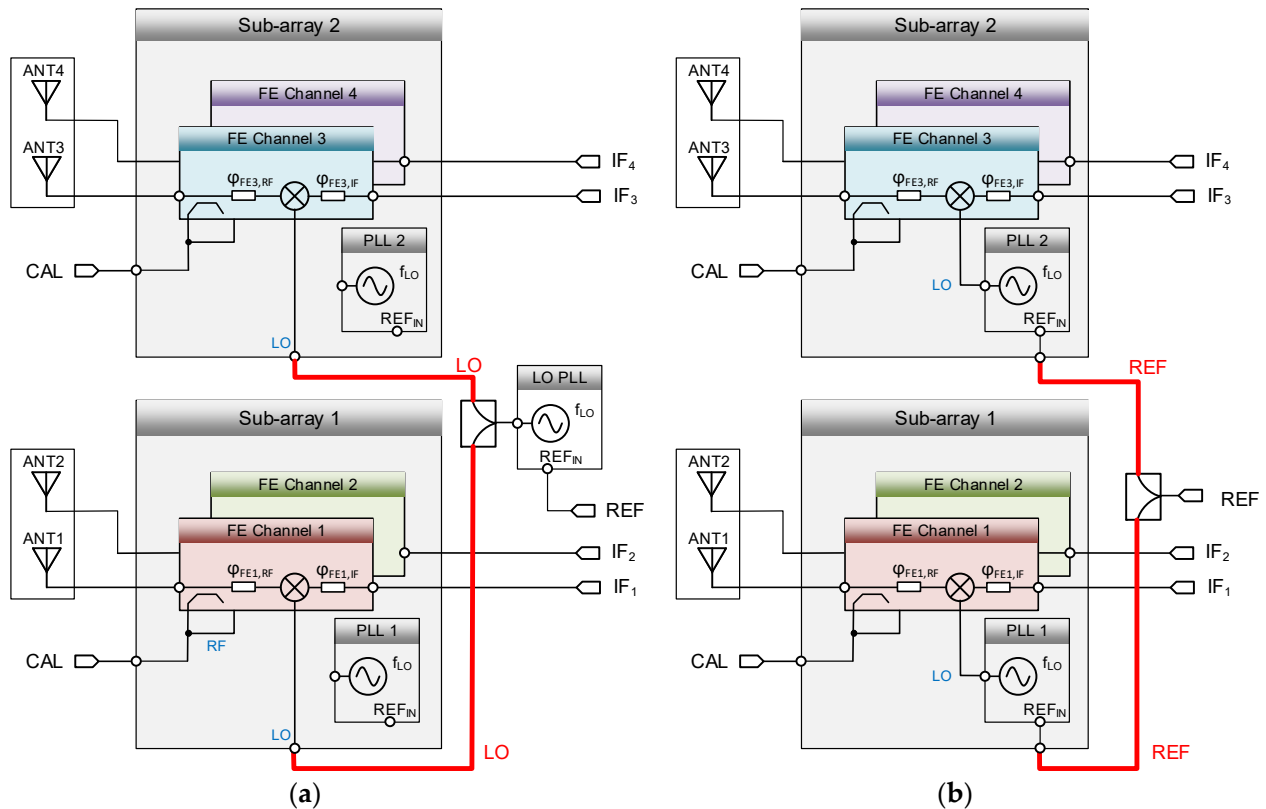


Figure 4. Options for LO signal distribution: (a) distribution of a common REF signal and separate LO generation at each sub-array; (b) common LO generation in a single PLL module and distribution of the LO signals to both sub-arrays.

For the REF signal distribution, despite the lower phase imbalance at both sub-arrays due to the lower frequency, the multiplication by the frequency synthesizer leads to the same total phase imbalance as for the direct LO signal distribution. Therefore, the electrical properties in terms of phase imbalance of both concepts are similar.

In the case of the REF signal distribution, the internal PLL of the ASIC is used to synthesize the LO signal. Using the internal PLL, the phase noise of the synthesized LO signal amounts to about -82 dBc/Hz @ 10 kHz offset and -110 dBc/Hz @ 1 MHz offset from the carrier frequency. In the case of the LO distribution, by using a dedicated PLL synthesizer IC (e.g., LTC6948 from Analog Devices, Wilmington, DE, USA), lower phase noise values of about -100 dBc/Hz @ 10 kHz and -130 dBc/Hz @ 1 MHz are achievable. The LO phase noise limits the carrier-to-noise ratio (CNR) of the output signal, narrowing the carrier tracking loop bandwidth and limiting the effective integration interval [17]. Therefore, the importance of this parameter for the system performance is an additional criterion to decide between both approaches.

A number of additional criteria have been weighted against each other to decide between the two options for the LO signal generation, including hardware and software

efforts and costs; the low frequency of the REF signal allows twisted-pair cables to be employed instead of coaxial cables, which leads to a reduction in costs and weight. Another advantage of the REF signal distribution is that only one cable is required in contrast to the LO signal distribution, which needs to cover two frequency bands and thus two PLL modules, which have to be set up and monitored by additional software. Table 1 summarizes the pros and cons of both concepts. Eventually, the lower hardware and software efforts at similar RF characteristics led us to the decision to use the REF signal distribution for the generation of the LO signal at each sub-array.

Table 1. Comparison between REF-signal and LO-signal distribution.

	REF-Signal Distribution	LO-Signal Distribution
Hardware and software effort	(+) internal ASIC PLLs (+) programming via ASIC control software	(−) two additional PLL modules required (−) additional control software and lock-detect monitoring
Number of cables	(+) 1x twisted pair	(−) 2x coaxial cable
Phase imbalance due to cable length	(o) similar to LO-signal distribution	(o) depends on cables
Cable loss	(+) lower	(−) higher
LO phase noise	(−) higher, due to usage of the internal frontend ASIC PLL	(+) lower, due to usage of an advanced external PLL IC

3.2.2. CAL Signal Distribution

For calibration, an artificial GNSS signal is generated in the digital baseband and applied to all receiver chains. The calibration signal is generated in the IF domain at $f_{IF} \approx 70$ MHz and must be up-converted to the RF frequency bands with the synthesized LO signals. This guarantees phase coherence between the real GNSS receiver signals and the artificial GNSS calibration signal.

Upon down-conversion, all signals share the same IF frequency band. Similar to the LO signal distribution, two options also exist for the CAL signal distribution. Either the calibration signal is distributed to the subarrays and up-converted there (CAL signal distribution at IF), as illustrated in Figure 5a, or it is up-converted centrally and then distributed to the subarrays (CAL signal distribution at RF), as shown in Figure 5b.

Actually, the hardware effort on a sub-array level is larger for the CAL signal distribution at IF because an additional up-converter is required for each frequency band at each sub-array; in a future re-design, the up-converters could be integrated into the ASIC. In contrast, for the CAL signal distribution at RF, two LO signals have to be generated and distributed, with similar implications for the hardware and software efforts, as discussed, for the LO signal distribution.

For a comparison of the phase imbalance between the CAL signals at both sub-arrays, similar considerations are applicable as for the LO signal distribution, as the calibration signal is connected to the sub-arrays by cables in both cases. Therefore, the same constraints on length differences and temperature changes apply. The lower frequency of the CAL signal at $f_{IF} = 70$ MHz in comparison to the more than 20-fold higher RF signal in the L-band results in a correspondingly lower phase imbalance between the sub-arrays for a given change in the electrical length of the cables. This advantage, however, is lost upon up-conversion with the LO signal at each subarray. Additionally, it turns out that the calibration concept originally applied to the 2×2 URA cannot be applied to the distributed array in the same way. Rather, calibration with an artificial GNSS signal can be achieved at sub-array level only. There, the phase balance between the calibration signals for each receiver channel can be guaranteed by the use of a passive signal distribution network.

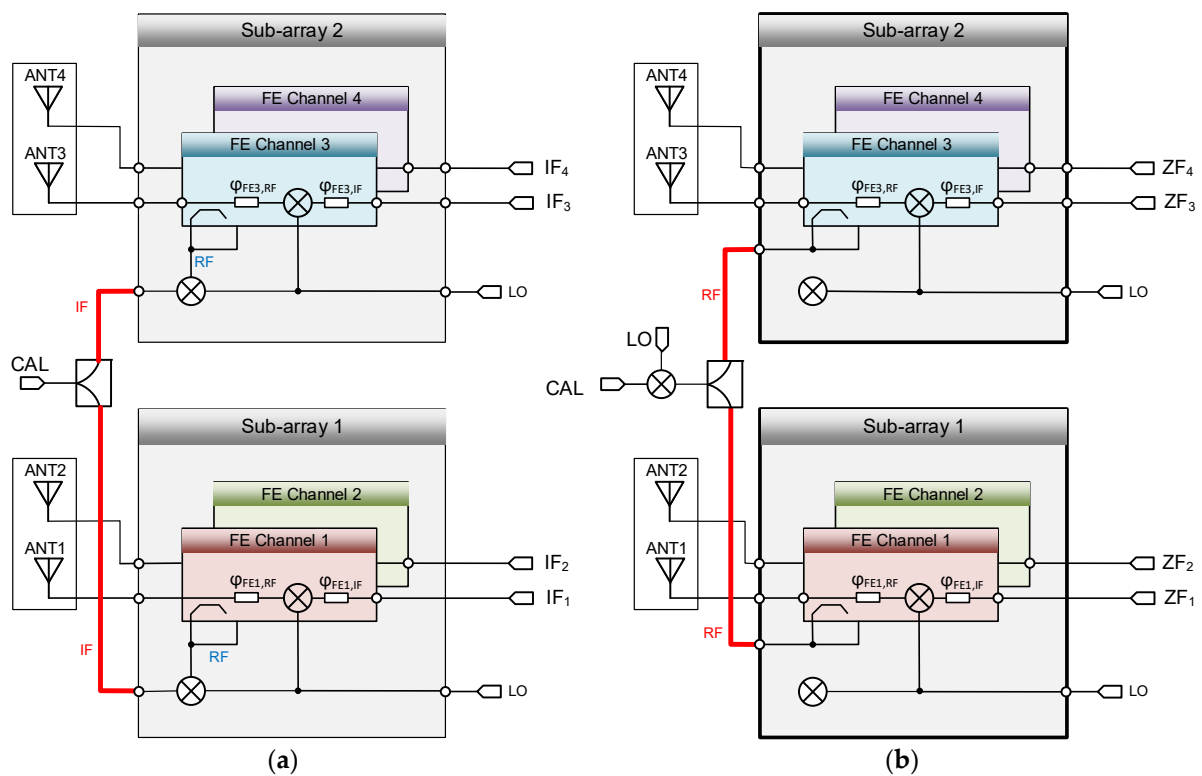


Figure 5. Calibration signal distribution options: (a) distribution of a common CAL signal to both sub-arrays, where it is up-converted using the local LO signals; (b): the CAL signal is generated in a common module and the radio frequency (RF) signal is distributed to each sub-array.

Table 2 compares the different properties of both CAL signal distribution concepts. Because of the lower effort and implementation costs, we selected the CAL distribution at IF for the compact distributed GNSS receiver.

Table 2. Comparison between CAL-signal distribution at IF and RF.

CAL Signal Distribution	... at IF	... at RF
Hard- and software effort	(o) usage of internal ASIC PLLs	(−) 2 additional PLL modules required inside the car
	(+) programming via ASIC control software	(−) additional control software and lock-detect monitoring
Number of cables	(o) up-converter required at sub-arrays	(o) up-converter required in PLL module
	(+) 2x twisted Pair	(−) 2x coaxial cable
Phase imbalance due to cable length	(o) similar to distribution at RF due to LO phase imbalance	(o) directly dependent on length difference between the RF cables towards each sub-array

The full calibration of the distributed array must be conducted in the digital domain, resulting in a blind or hybrid calibration concept [18]. In [19], we proposed a solution to determine the accurate position and attitude of a multi-antenna system without the explicit use of a dedicated calibration signal. The capability to mitigate interference sources with the distributed array receiver was presented in [3,20].

A photograph of one sub-array is shown in Figure 6. The sub-array module consists of two stacked printed circuit boards, one containing the antenna network and the other the

RF frontend including the ASIC. The size measures about $10\text{ cm} \times 5\text{ cm} \times 2\text{ cm}$. With these dimensions, an integration into typical automotive installation spaces appears feasible.

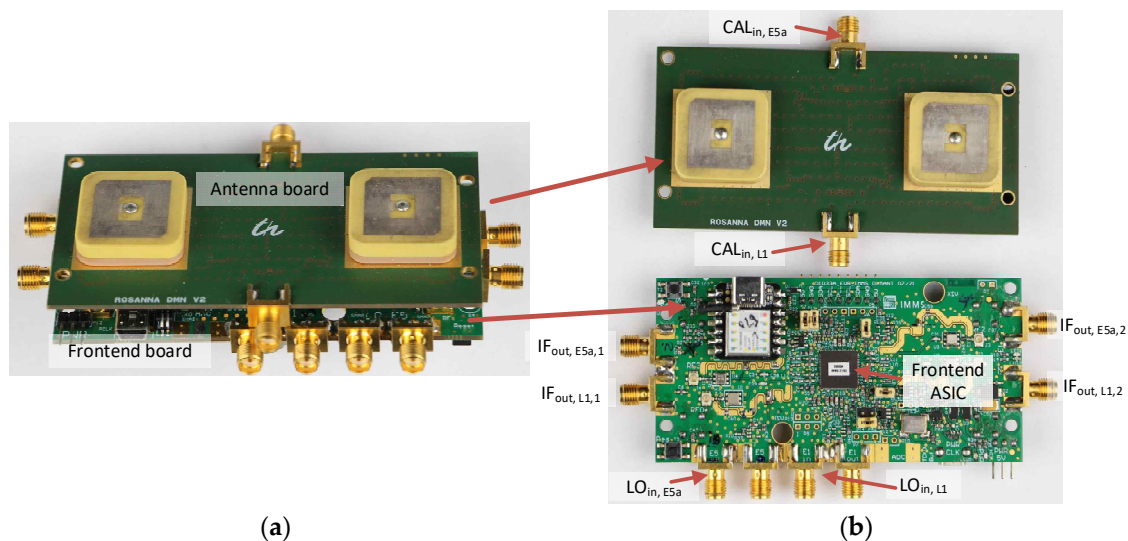


Figure 6. (a) Receiver sub-array consisting of antenna and frontend board (the module height is 2 cm); (b) antenna board (top) and frontend board with dedicated GNSS receiver ASIC (bottom) with CAL and LO signal input connectors.

4. Conclusions

In this paper, different concepts for the distribution of the calibration and local oscillator signals to distributed sub-arrays of a dual-band multi-antenna GNSS receiver were compared in terms of the resulting system performance and practical implementation issues. RF performance as well as hardware and software efforts and costs were reflected in our design considerations. The distributed arrangement of sub-arrays necessitates layout cable connections, which challenge the phase coherence required for the array signal processing. Despite the similar performance in terms of phase imbalance between the signals at both sub-arrays, the REF signal distribution and the CAL signal distribution at IF were eventually selected. This decision is based on the most important specification parameters of the intended application, installation space and cost, while considering the targeted system performance. For other applications, the required application parameters could lead to a different conclusion. Accordingly, the criteria compared in Tables 1 and 2 provide guidance for the selection process. The distributed system approach facilitates the integration of robust GNSS receivers into the limited installation spaces available in series cars and thus opens the market for an improved level of navigation safety.

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References

1. Kaplan, E.; Hegerty, C. *Understanding GPS/GNSS: Principles and Applications*, 3rd ed.; Artech: London, UK, 2017.
2. Ruegamer, A.; Kowalewski, D. Jamming and Spoofing of GNSS Signals—An Underestimated Risk?! In Proceedings of the FIG Working Week 2015, Sofia, Bulgaria, 17–21 May 2015.
3. Brachvogel, M.; Niestroj, M.; Zorn, S.; Meurer, M.; Hasnain, S.N.; Stephan, R.; Hein, M.A. Jamming an uncalibrated GNSS array receiver of distributed antenna elements for concealed installation in passenger cars. In Proceedings of the 2020 European Navigation Conference (ENC), Dresden, Germany, 23–24 November 2020.
4. Kurz, L.; Taşdemir, E.; Bornkessel, D.; Noll, T.G.; Kappen, G.; Antreich, F.; Sgammini, M.; Meurer, M. An architecture for an embedded antenna-array digital GNSS receiver using subspace-based methods for spatial filtering. In Proceedings of the 2012 6th ESA Workshop on Satellite Navigation Technologies (Navitec 2012) & European Workshop on GNSS Signals and Signal Processing, Noordwijk, Netherlands, 5–7 December 2012; pp. 1–8. [\[CrossRef\]](#)
5. Amoroso, F. Adaptive A/D Converter to Suppress CW Interference in DSPN Spread-Spectrum Communications. *IEEE Trans. Commun.* **1983**, *31*, 1117–1123. [\[CrossRef\]](#)
6. Grabowski, J.; Hegarty, C. Characterization of L5 Receiver Performance Using Digital Pulse Blanking. In Proceedings of the 15th International Technical Meeting of The Institute of Navigation (ION GPS 2002), Portland, OR, USA, 24–27 September 2002; pp. 1630–1635.
7. Dabak, Ö.C.; Erdem, F.; Sönmez, T.; Alatan, L.; Koç, S.S. Interference suppression in a GPS receiver with 4 element array design and implementation of beamforming algorithms. In Proceedings of the IEEE/ION Position, Location and Navigation Symposium (PLANS), Savannah, GA, USA, 11–14 April 2016.
8. Curran, J.T.; Bavaro, M.; Fortuny-Guasch, J. Null-Steering Antennas. *GPS Word. GPS World Mag.* **2016**, *27*, 62–68.
9. Irteza, S. Compact Adaptive Planar Antenna Arrays for Robust Satellite Navigation Systems. Doctoral Thesis, TU Ilmenau, Ilmenau, Germany, 2016.
10. Meurer, M.; Konovaltsev, A.; Appel, M.; Cuntz, M. Direction-of-Arrival Assisted Sequential Spoofing Detection and Mitigation. In Proceedings of the 2016 International Technical Meeting of The Institute of Navigation, Monterey, CA, USA, 25–28 January 2016; pp. 181–192. [\[CrossRef\]](#)
11. Ibraheam, M. Design and Testing of Compact Dual-band Dual-polarized Robust Satellite Navigation Antenna Arrays. Doctoral Thesis, TU Ilmenau, Ilmenau, Germany, 5 June 2019.
12. Brachvogel, M.; Niestroj, M.; Zorn, S.; Meurer, M.; Hasnain, S.N.; Stephan, R.; Hein, M.A. A new array concept using spatially distributed subarrays for unambiguous GNSS interference mitigation in automotive applications. *Navigation* **2020**, *67*, 23–41. [\[CrossRef\]](#)
13. Hasnain, S.N.; Stephan, R.; Brachvogel, M.; Meurer, M.; Hein, M.A. Performance testing of a distributed automotive satellite navigation array with jammer in virtual environment. In Proceedings of the 15th European Conference on Antennas and Propagation (EuCAP), Dusseldorf, Germany, 22–26 March 2021; pp. 1–5. [\[CrossRef\]](#)
14. Ibraheam, M.; Bieske, B.; Blau, K.; Schäfer, E.; Jäger, A.; Butt, S.I.; Stephan, R.; Hein, M.A. Feasibility of dual-polarized antenna arrays for GNSS receivers at low elevations. In Proceedings of the 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, 19–24 March 2017; pp. 857–861. [\[CrossRef\]](#)
15. Abracon, Datasheet Dual-band Antenna APAKM25075. Available online: <https://abracon.com/datasheets/APAKM25075-SGL5.pdf> (accessed on 14 April 2023).
16. Times Microwave Systems, Current Innovation in Phase Stable Coaxial Cable Design. Microwave Product Digest. Available online: <https://timesmicrowave.com/current-innovations-in-phase-stable-coaxial-cable-design/> (accessed on 11 April 2023).
17. Serna, E.P.; Thombre, S.; Valkama, M.; Lohan, S.; Syrjälä, V.; Hurskainen, H.; Nurmi, J. Local Oscillator Phase Noise Effects on GNSS Code Tracking. *InsideGNSS* **2010**, *5*, 52–62.
18. Brachvogel, M.; Niestroj, M.; Meurer, M. Full Wideband Calibration for an Array of Spatially Distributed Subarrays. In Proceedings of the IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, USA, 24–27 April 2023.

19. Zorn, S.; Siebert, C.; Niestroj, M.; Brachvogel, M.; Meurer, M. Accurate Position and Attitude Determination in a Severe Multipath Environment Using an Uncalibrated Multi-Antenna-System. In Proceedings of the 2020 IEEE/ION Position, Location and Navigation Symposium (PLANS), Portland, OR, USA, 20–23 April 2020; pp. 1247–1255. [[CrossRef](#)]
20. Brachvogel, M.; Niestroj, M.; Schoenbrod, S.; Meurer, M.; Hasnain, S.N.; Stephan, R.; Hein, M.A. Interference and Jammer Suppression of High Bandwidth Signals using an Array of Spatially Distributed Subarrays. In Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), St. Louis, MO, USA, 20–24 September 2021; pp. 3812–3823. [[CrossRef](#)]

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