Objectives and overview

The transport of goods, the observation of public events, the measurement of buildings, the tasks and the inspection of agriculture – these are only a few of the ways in which mobile systems such as multicopters can be used. If these aerial systems are to be sent out to do their job without human intervention in situations where security and safety are critical, there will always be a need for navigation that is robust, absolutely accurate and proof against interruption or hacking: i.e., it can rely on features known in the trade as “anti-collision”, ”anti-grounding“, ”geofencing“, ”coming home“ and “autoland“. This is clear from the example of civilian UAVs (unmanned aerial vehicles). It is only by dint of spot-on, fail-safe navigation that a prescribed route can be followed so exactly that collisions are avoided, flying height kept within limits, no-fly zones avoided, and, in the event of a loss of communication, homing and automatic landing achieved – without any breach of the laws that apply.
For safety-critical autonomous navigation purposes, commonly and commercially available satnav equipment is out of the question for two reasons: potential breaks or errors in the positioning function, and susceptibility to interference. Satnavs receive their signals from satellites more than 20,000 kilometres away, which means those signals are very weak on arrival and that they are susceptible to the deliberate interference known as GNSS-jamming from transmitters able to send signals perhaps more than a hundred times their strength. Hijacking of the flying object itself is also a possibility.

For these reasons, as early as in the years 2010 – 2013, it fell to the German Aerospace Centre (DLR), the Ilmenau University of Technology, the RWTH Aachen and IMMS to research new designs, technology and algorithms for the sort of more compact adaptive group antennas necessary to eliminate satnav signal disruption. These are capable of fulfilling very high interference-mitigation specifications, but those developed so far were too large and heavy for actual mobile use. A receiving unit was designed by IMMS and partners which was only a quarter of the size of a conventional group antenna but had the same number of individual elements. It has proved the applicability of the signal treatment techniques. IMMS’ part was to develop the receiver front end circuit forming the link between the antenna array and the digital evaluation software.

KOSERNA was started as a follow-on project in 2014. In it, the same partners have constructed an industrial prototype on the basis of the results achieved in 2013 in conjunction with the antenna engineering company Antennentechnik Bad Blankenburger GmbH. In parallel, the partners have worked on the issues of significantly increased accuracy and robustness for a novel receiver unit. For it, IMMS as subcontractor to Ilmenau TU (Technische Universität) has extended the frontend circuits and transferred the new principles onto a second frequency band.

The new prototype was fully tested at the Automotive Galileo Test Environment (GATE) in Aldenhoven, Germany in 2016. Good results were obtained in a number of test drives in real situations exposed potentially to disruption with which the standard GPS equipment commercially available would fail to cope.
The solution in detail

Review of the first prototype: the basis of a new receiver
If navigation systems that have high-performance, reliable components are too large, they will not be marketable. In view of the fact that classic group antennas with four individual antennas in a square array have an outside edge of about 30 centimetres, the components for the 4-antenna array in the initial project were considerably reduced in size.

Why group antennas at all?
Combination of several antennas is absolutely necessary if interfering or reflected signals are to be successfully suppressed and the UAV enabled to navigate precisely. Group antennas function in a way reminiscent of the human brain’s ability to judge direction through a noise heard with the ears. They detect interference signals, analyse them to establish the direction of the source, and block them out. This is achieved by means of customised electronics and algorithms which permit beamforming – adaptive shaping and controlling of the signal beams. If there are four channels, up to three sources of interference can be blocked.

What stops the group antennas from being made tinier and tinier?
The distance between the grouped antennas will usually be approximately half the wavelength of the signals to be received. To achieve smaller antennas, the distances between the individual elements have to be reduced. However, if each element is less than half a wave length from the next, the coupling will be intensified. This interaction between the individual detectors decreases the sensitivity of the group to signal direction, defeating the object.

So what was done?
A solution to this basic problem was found in the project stage completed for 2013: from that R&D came a satellite receiver with a group antenna which was reduced to 15x15 cm², had 4 channels, one type of polarisation and a single reception frequency band. Special decoupling and adaptive networks together with receiver circuit and the appropriate algorithmic signal processing served to compensate for the negative coupling effects. IMMS had developed the circuit which amplified the signals (with low noise) and converted them to a frequency range around 75 MHz, in which they could be directly put through an ADC, then subjected to digital processing and evaluation.
Challenges facing the new receiver

Why more channels?
With the new receiver system being developed from 2014, spot-on navigation must be possible without any failure caused by interference, disturbance and noise. And it would also have to be made even smaller. Again, the receiver has four grouped antennae. But the number of channels has been quadrupled, raising the number of degrees of freedom to 16 from four. This has been achieved by changing from one to two reception bands and from one to two types of polarisation. Redundancy is the welcome result, meaning that absent or disrupted signals can be compensated for.

With the second frequency band on which to receive Galileo E5a-type signals, IMMS has increased the number reception channels from four to eight. Furthermore, the new receiver processes LHCP (left handed circular polarisation) in addition to RHCP (right handed circular polarisation) signals for each of the frequency bands, which is what is meant by dual polarisation. The number of channels is thus effectively doubled, to 16.

Why dual polarisation?
Satellite signals are of their nature an RHCP of the electromagnetic waves. They pass through the atmosphere in a straight line. However, when the satellite is low over the horizon, LHCP signals arrive in addition at the antenna which is horizontal. Likewise, circular polarisation changes for every reflection from right to left or vice versa. For these reasons, the newly designed system processes not only standard RHCP signals, but also those with LHCP. Another potential source of disruption eliminated.

The IMMS contribution
The quadrupling, above all, brought with it much more complex challenges on many fronts: the networks used in decoupling and adaptation, the adapted algorithmic signal processing, and thus, also, for the receiver frontend circuit which IMMS developed as the link between the group antenna and the digital signal analysis electronics. What IMMS developed was an ASIC and a circuit board.

It was necessary to reduce the size of the new receiver to a 10 cm square. The connector for the signals at the antennae was a standard jack, one centimetre wide, for the 16 channels with 16 inputs and outputs distributed over two frontend circuit boards (see Fig. 2). The essential core of each of the two PCBs is the specially developed ASIC.
Development of the frontend ASIC

The receiver has to be capable of suppressing interfering signals which may be more than 100 times stronger than those from a satellite. For this, the entire receiver channel must have strong linearity across a large dynamic range.

The receiver circuit at the frontend handles the weak, high-frequency satellite signals in such a way that they can be subjected to digital processing at the next stage and be sent through the algorithms that will suppress interference. In the frontend circuit, the satellite signals are coherently converted and amplified. The amplification can be set in four levels between 44 dB and 80 dB, which avoids any overdrive in the ensuing ADC (analog-to-digital converter).

Into the new chip, in contrast to the earlier one, IMMS has integrated two frequency bands on one ASIC. The chip has been optimised with insulation of 25 dB for eight reception channels because it is necessary to avoid crosstalk between channels and also because space is so limited on the ASIC. This insulation has been achieved by the spatial disposition of the channels and varied intermediate frequencies. In the complete system, two of these ASICs are employed so that the signals in 16 channels can be processed.

The two identical types of chip on the two circuit boards must interact to ensure that frequency conversion takes place in a coherent fashion using a shared local...
oscillator on the eight paths in each frequency band. For each of these bands there is a frequency synthesiser on the chip. The two chips are configured so flexibly from a digital interface (I2C) that at any one time only one chip acts as frequency synthesiser on behalf of both, creating the local oscillators and distributing them to the second chip. It is this master-slave arrangement that makes coherent frequency conversion feasible for all the channels.

The digital I2C interface has many more settings available so that, among other things, energy can be saved by switching off channels not in use, or manufacturing tolerances associated with the technology can be compensated for. In this connection, the amplification of channels that belong together in a frequency band can be calibrated within a tolerance of +/- 1 dB. The configuration desired for the ASIC is automatically loaded from a microprocessor situated on the circuit board when the receiver is switched on.

Development of the frontend board
For the frontend, IMMS has designed, layouted, assembled and evaluated the circuit boards. The ASICs, each with 119 pins, were sealed directly onto the board after first being stuck on and bonded (Chip-on-board technology).
Each of the two boards implements all peripherals that are necessary for operation of either ASIC within the receiver. In addition, the design of the board is such that it has been possible to use it to characterise the ASIC.

Each board provides all necessary supply voltages and a reference oscillator. So that the satellite signals pass from the antenna to the input of the frontend ASIC with little noise, the complex resistances of both have to matched. Wiring and capacitors on the PCBs are used for this. Their performance has been verified by S-parameter measurement using a VNA (vector network analyser) (see Fig. 4). This is the means of achieving the lowest possible signal loss in the two satellite frequency bands (E1 and E5a), as is shown from the minima on the graph. There are also LEDs on the boards to indicate the current status of the analogue frontend.

The board acting as master contains an MCU to load the settings for both ASICs and for the interaction of the two chips described above as the means of achieving coherent frequency modulation. The different amplification levels indicated above can be selected by means of DIP switches for the two frequency bands independently of each other.

**Characterisation and testing**

Comprehensive measurements carried out at IMMS have shown that all the specifications have been fulfilled or more than fulfilled by the design of the ASIC and board. The large dynamic range and excellent linearity necessary for suppression of interference has been proven by means of S-parameter and large signal measure-
Overall amplification can be set up to 80 dB and the relation between output signal and input signal is linear up to power of 4 mW or 1.5 Vpp. This being the case, the digitised signals and further processing can be managed optimally.

It has been shown by noise measurements for the individual reception channels that the IMMS frontend has sufficient reception sensitivity. Comparative noise measurements which took place at the noise measurement lab of Ilmenau TU have confirmed the measurements taken at IMMS. To prove that the frequency down-conversion had no adverse effect on accurate copying of the satellite signals and brought in no distortion, the frontend output signals were mixed back into the original frequency situation of the E1 band using a special calibration board. These signals were then broadcast in a shielded measuring chamber at IMMS and recorded with a standard GPS receiver, an Android device containing an app appropriate to analysis of the individual satellite signals. As shown in the example here, the position was determined to an accuracy of within 3 metres which is proof of high signal quality, see Fig. 5.

In measurements during September 2016, the partners in Ilmenau put the entire reception system to the test. Antenna arrays of Ilmenau TU were used. Correct functioning of both polarisation options for the group antenna was tested in respect of GPS signals, see Fig. 1.

**Future prospects**

The frontend developed by IMMS has met or exceeded the demanding specifications concerning noise and resistance to disruptions. On test drives in real situations at the GATE in Aldenhoven Germany, in October 2016, results were obtained using...
the complete system that confirmed position accuracy of less than one metre and showed the system was proof against disruption.

To bring the frontend up to meeting industrial conditions, IMMS would have to adapt the method of packaging and bonding of the ASIC. It would also be possible to make the board even smaller and lighter in weight. More compact jacks would help achieve this, or integration into the chip of functions that are present on the PCB. It would, furthermore, be possible to base future development on the present complete system and meet the needs of other applications such as those of driverless cars, for which the challenges and conditions of use are different.

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Publications


**Motivation und Überblick**


Kommerziell verfügbare Satellitennavigationsempfänger kommen wegen möglichen Ortungsfehlern oder -abbrüchen und wegen mangelnder Störsicherheit für autonome und sicherheitskritisches Navigieren nicht in Betracht. Da Satellitensignale über eine Entfernung von über 20.000 km übertragen werden, kommen sie mit einer geringen Leistung an. Somit kann der Empfang durch Störsender, die um mehr als
das Hundertfache stärker als Satellitensignale sein können, bewusst beeinträchtigt werden. Darüber hinaus kann das Flugobjekt entführt werden.

Daher hatten das Deutsche Zentrum für Luft- und Raumfahrt (DLR), die TU Ilmenau, die RWTH Aachen und das IMMS bereits von 2010 bis 2013 neue Konzepte, Technologien und Algorithmen erforscht, um adaptive Gruppenantennen zur störungsfreien Satellitennavigation kompakter zu gestalten. Solche Antennen erfüllen sehr hohe Anforderungen bezüglich der Störsicherheit, waren bis dato jedoch für den mobilen Einsatz zu groß und zu schwer. Die Partner haben eine Empfangseinheit realisiert, die nur ein Viertel so groß ist wie eine konventionelle Gruppenantenne mit gleicher Anzahl an Einzelelementen und die die Anwendbarkeit der entwickelten Verfahren demonstrierte. Das IMMS hatte die Empfänger-Frontend-Schaltung als Bindeglied zwischen der Gruppenantenne und der digitalen Auswerteelektronik entwickelt.

Im 2014 gestarteten Anschlussprojekt KOSERNA haben die o.g. Partner auf dieser Grundlage einen industriellen Prototyp mit der Firma Antennentechnik Bad Blankenburger GmbH aufgebaut und darüber hinaus an einer wesentlich genaueren und deutlich robusteren Weiterentwicklung der Empfangseinheit gearbeitet. Das IMMS hat für die neue und nochmals verkleinerte Empfangseinheit im Unterauftrag der TU Ilmenau die Frontend-Schaltungen erweitert und die neuen Konzepte auf ein zweites Frequenzband übertragen.


Die Lösung im Detail

Rückblick auf die erste Entwicklung: Basis für den neuen Empfänger

Wozu braucht man Gruppenantennen?


Warum kann man Gruppenantennen nicht beliebig verkleinern?


Wie sah die Lösung aus?

Dieses Grundproblem wurde bereits mit der seit 2013 vorliegenden Projektentwicklung gelöst: F&E-Ergebnis war eine auf 15 x 15 cm² verkleinerte Empfangseinheit für Satellitensignale mit vier Kanälen, mit einer Polarisation und mit einem Empfangsband. Spezielle Entkoppel- und Anpassnetzwerke, die Empfängerschaltung und eine angepasste algorithmische Signalverarbeitung kompensieren die negativen Effekte der Verkopplung. Das IMMS hatte die Schaltung entwickelt, die die Satellitensignale rauscharm verstärkt und in einen Frequenzbereich bei 75 MHz umsetzt, wo sie direkt über einen Analog-Digital-Wandler digital aufbereitet, verarbeitet und ausgewertet werden.

Anforderungen an die neue Empfangseinheit

Wozu braucht man mehr Kanäle?

Das neue, 2014 in Angriff genomme Empfangssystem sollte eine wesentlich genauere Navigation ermöglichen, dabei unempfindlich gegenüber Störern, Interferenzen und Rauschen arbeiten und nochmals verkleinert werden. Die Empfangseinheit ist nach wie vor mit vier gruppierten Einzelantennen ausgestattet. Die Zahl der Kanäle wurde jedoch vervielfacht und damit die Anzahl der Freiheitsgrade von vier...
auf 16 erhöht. Erreicht wird dies durch die Erweiterungen von einem auf zwei Empfangsbänder und von einer auf zwei Polarisationen. Das erzeugt Redundanzen, die Ausfälle und Störungen ausgleichen können.

Mit dem zweiten Frequenzband für den Empfang von Galileo-E5a-Signalen erhöht sich die Anzahl der Empfangskanäle von vier auf acht. Für jedes der beiden Frequenzbänder wird der links- und rechtsdrehende zirkulare Signalanteil getrennt verarbeitet und damit die sog. Dualpolarisation erreicht. Die Kanalzahl verdoppelt sich dadurch auf 16.

**Warum braucht man Dualpolarisation?**


**Beitrag des IMMS**

Vor allem die Vervierfachung der Anzahl der Kanäle bedeutete wesentlich komplexe und schärfere Anforderungen für die Entkoppel- und Anpassnetzwerke, die angepasste algorithmische Signalverarbeitung und damit auch für die Empfänger-Frontend-Schaltung, die das IMMS als Bindeglied zwischen Gruppenantenne und digitaler Auswertelektronik erarbeitet hat. Die Entwicklung des IMMS beinhaltet eine anwendungsspezifische integrierte Schaltung (ASIC) und eine Platine.

Die Größe der neuen Empfangseinheit sollte nochmals verkleinert werden auf 10 x 10 cm². Der Anschluss der Antennensignale erfolgte mittels einen Zentimeter breiten Standard-Steckverbindern für die 16 Kanäle mit 16 Ein- und 16 Ausgängen, die auf zwei Frontendplatinen verteilt werden (siehe Abb. 2). Kern der beiden Platinen ist jeweils der neuentwickelte ASIC.

**Entwicklung des Frontend-ASIC**

Die Empfangseinheit soll Störer unterdrücken können, die über 100 Mal stärker sind als das Satellitensignal. Dazu muss der gesamte Empfangskanal in einem großen Dynamikbereich eine hohe Linearität aufweisen.


Um die kohärente Frequenzumsetzung mit einem gemeinsamen Lokaloszillator zwischen den acht Pfaden je Frequenzband sicherzustellen, müssen die zwei identisch aufgebauten Chips auf den zwei Platinen interagieren. Auf dem Chip gibt es für jedes Frequenzband einen Frequenz-Synthesizer. Die Chips werden über eine digitale Schnittstelle (I²C) so flexibel konfiguriert, dass nur einer die Frequenz-Synthesizer-Funktion für beide übernimmt, die Lokaloszillatoren erzeugt und an den zweiten
Chip verteilt. Durch diesen Master-Slave-Betrieb ist die kohärente Frequenzumsetzung für alle Kanäle möglich.


**Entwicklung der Frontend-Platine**

Das IMMS hat die Leiterplatten entwickelt, bestückt und in Betrieb genommen. Die ASICs mit je 119 Pins wurden als Chip-On-Board-Aufbau direkt auf die Platine geklebt, gebondet und vergossen.

Die beiden Platinen implementieren jeweils alle peripheren Komponenten, die für den Betrieb der beiden ASICs in der Empfangseinheit nötig sind. Darüber hinaus wurde die Platine so gestaltet, dass sie für die Charakterisierung des ASICs verwendet werden konnte.

Eine Platine stellt alle benötigten Versorgungsspannungen und einen Referenzoszillator bereit. Um die Satellitensignale von der Antenne zum Eingang des Frontend-ASICs verlustarm zu übertragen, müssen deren komplexe Widerstände aneinander...
Anpassung werden. Dies wird mit Leitungselementen und Kondensatoren auf der Platine realisiert und wurde durch S-Parameter Messungen mit einem vektoriellen Netzwerkanalysator verifiziert (siehe Abb. 4). Damit werden geringstmögliche Übertragungsverluste in den beiden Satellitenbändern E1 und E5a erreicht, was durch die Minima in den Kurven im Diagramm dargestellt wird. Zusätzlich zeigen LEDs den aktuellen Status des analogen Frontends an.

Die Master-Platine enthält einen Mikrokontroller, der die Einstellungen beider ASICs lädt und die oben beschriebene Interaktion der beiden Chips zur kohärenten Frequenzumsetzung sicherstellt. Die oben genannten Stufen für die Verstärkung können über DIP-Schalter unabhängig für die beiden Frequenzbänder ausgewählt werden.

Charakterisierung und Test


Die ausreichende Eingangsempfindlichkeit des IMMS-Frontends wurde anhand von Messungen der Rauschzahlen der einzelnen Empfangskanäle nachgewiesen. Vergleichende Rauschmessungen fanden parallel dazu am Rauschmessplatz der TU Ilmenau statt und bestätigten die am IMMS ermittelten Messergebnisse.

Mehr zu Test und Charakterisierung auf www.imms.de.

In Kombination mit den Antennenarrays der TU Ilmenau haben bei einer Messkampagne im September 2016 die Ilmenauer Partner das gesamte Empfangssystem in beiden Polarisationsvarianten der Gruppenantenne auf korrekte Funktion für GPS-Signale getestet, siehe Abbildung 1.

**Ausblick**


Darüber hinaus sind auf dieser Basis Weiterentwicklungen des Gesamtsystems u.a. für weitere Anwendungen möglich, wie z.B. für autonomes Fahren, die andere Randbedingungen und Anforderungen mit sich bringen.

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Publikationen


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