Executive Summary:

The GRAMMAR project, established by DLR, ACORDE, and TUT, represented a highly innovative approach developing a prototype GNSS receiver aimed at mass-market applications with the widest potential exploitation. The project main goals were

- Developing a prototype mass market GNSS receiver using a single chip dual frequency front-end and an FPGA based baseband allowing for rapid prototyping of advanced algorithms
- Identifying, evaluating and simulating enhanced algorithm concepts for next generation mass-market receivers

Given these goals, GRAMMAR has achieved the following results and innovations:

GRAMMAR identified a lack of requirements for mass-market GNSS receivers in the public literature. Hence, we carried out original research leading to several publications, e.g., studies on analog bandwidth or phase noise requirements of GNSS receivers.

The initial integration of the radio front-end from the GREAT project and TUT's baseband design was not performed fully successful. Hence, additional radio front-ends using commercial-of-the-shelf (COTS) components and USB interfaces were developed.

The radio front-end development included two foundry runs for a single chip monolithic microwave integrated circuit (MMIC) and COTS radio front-ends for baseband testing and demonstrating ACORDE's future products and services. The first MMIC was an evolution from GREAT with tighter integration and more flexibility. The second MMIC implemented a dual-band receiver with much more advanced technology, e.[*]g[/*]., large power reduction in most front-end stages and a new image-rejection filter. The results showed very good performance in most subcircuits. Due to some problems, only the second MMIC could be partially used. Thus, a third MMIC was designed to have a functional prototype at least after the project end showing ACORDE's commitment.

In the baseband implementation, the main problems were related to integration of radio front-ends with the baseband FPGA, dual-frequency tracking, and Galileo data decoding. TUT has implemented a dual-frequency dual-system GPS L1/L5 Galileo E1/E5a receiver baseband processing unit, called TUTGNSS. It includes a tool to capture raw data streams along critical points in the baseband simplifying debugging. Currently, debugging and testing of the COTS radio front-ends integrated with the TUTGNSS on an FPGA continues to solve any remaining issues and to achieve the first main goal.

Enhanced algorithms in the baseband and for hybrid data fusion using INS, WLAN, and LTE as planned were researched and investigated. The algorithms were tested using DLR's newly developed channel model for joint positioning of GNSS and LTE. An LTE/OFDM test-bed and a prototype receiver with advanced algorithms were implemented by DLR and first measurements were conducted. The feasibility of complexity reduced multipath mitigation in an FPGA was shown. An ionospheric correction algorithm was developed and implemented in the GRAMMAR prototype. Thus, the second main goal was fully achieved.

The partners will exploit through licensing and participation in new projects IPR such as the open-source TUT Simulink Galileo E1 signal simulator, the TUTGNSS design, DLR's new channel model for joint positioning of GNSS and LTE, and DLR's 3GPP-LTE positioning platform. ACORDE created a specific GNSS-oriented division within the company with its own business plan and will commercially exploit an L1/L5 radio front-end with USB interface for SDR GNSS receivers, MMICs, and multi-frequency front-ends.

GRAMMAR applied for two patents, published more than 50 articles, and was presented at eight conferences and workshops in Europe and the USA. The project results were presented to international experts at the GRAMMAR final workshop during the International Conference on Localization and GNSS (ICL-GNSS) 2011. Through ICL-GNSS and the "GALILEO Positioning Technology" book, GRAMMAR has achieved a long lasting impact in the GNSS community.

Project Context and Objectives:

Building on the success of FP6 projects, in particular the GREAT project, GRAMMAR seeks to address the mass market receiver by extending the current state-of-the-art technologies for the mass market segment. Specifically, we are addressing the following gaps identified as obstacles for producing high-quality mass market receivers:

- No economic solutions for accurate dual-frequency RF and baseband hardware
- No existing GPS/Galileo receiver solutions
- Poor robustness and location availability in indoor and urban environments

The goals of GRAMMAR's technical work are:

- The development of a hardware prototype for a mass market receiver using a single chip dual frequency receiver and an FPGA based baseband allowing for rapid prototyping of advanced algorithms and techniques.
- The identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers.

We aim to produce functional prototypes of the receiver and its components, enabling practical testing and demonstration at the completion of the project.

Project Concept and Objectives

GRAMMAR represents a highly innovative approach to develop a prototype GNSS receiver, targeted at mass market applications, with the widest potential exploitation.

GRAMMAR will develop a library of IP blocks necessary to develop a prototype mass market receiver, including radio front-end, baseband control blocks and navigation algorithms.

GRAMMAR will develop a prototype receiver in the form of an evaluation board suitable for wide dissemination.

GRAMMAR will release firmware and software developed under open license terms to maximise its exploitation while remaining compliant with the overall EU policy for Galileo and FP7 as well as regulations of any partner.

With no constraints from commercial organisations, the majority of the research effort can be made available to GNSS community.

The prototype / evaluation platform will be based on a standard COTS FPGA board with an integrated ACORDE radio front-end. The prototype / evaluation platform could be made available as a standard package to interested parties. We expect this to include European SMEs, Universities and research firms interested in exploring GNSS with the potential to create user applications.

We will establish an online presence for supporting the evaluation platform.

GNSS is an increasingly important part in daily life for many EU citizens, in most cases through applications such as route guidance, tracking services, leisure, fleet management, emergency calls, theft protection for vehicles etc. The GSA's own figures suggest the value of the GNSS worldwide market of all applications is evaluated to be worth around 40 Billion USD in 2006 and expected to pass the 90 Billion USD by 2011. Three billion satellite navigation receivers are predicted to be in service by 2020.

EGNOS and Galileo will further develop Europe's position as a source of market leading innovation in the GNSS industry.

The early availability of low cost interoperable Galileo/GPS/EGNOS mass market receivers and end user terminals is therefore important for the success of Galileo.

Building on the success of FP6 projects, in particular the GREAT project, GRAMMAR seeks to address the mass market receiver by extending the current state-of-the-art technologies for the mass market segment.

Specifically, we are addressing the following gaps identified as obstacles for producing high-quality mass market receivers:

- No economic solutions for accurate dual-frequency RF and baseband hardware.
- No existing GPS/Galileo receiver solutions for mass market solutions using advanced features like dual frequency measurements.
- Poor robustness and location availability in indoor and urban environments.

The goals of GRAMMAR's technical work are:

- The development of a hardware prototype for a mass market receiver using a single chip dual frequency receiver and an FPGA based baseband allowing for rapid prototyping of advanced algorithms and techniques.
- The identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers.

We aim to produce functional prototypes of the receiver and its components, enabling practical testing and demonstration at the completion of the project.

Achieving these goals will result in the following benefits for the Galileo community:

- Public reports on the analysis of the GNSS market and current state-of-the-art technology for combined GPS/Galileo/EGNOS receivers.
- Reference solutions for GPS/Galileo/EGNOS hardware.
- Published advanced algorithms and methods suitable for mass market receivers.
- Increased know-how on sensor and network assistance possibilities.
- Increased visibility of Galileo/EGNOS activities within European Industry including SMEs.

GRAMMAR will address the objectives of the topic call:

- Conduct further R&D activities for core technologies related to interoperability.
- Galileo/GPS/EGNOS mass market receivers, addressing specific mass market segments.
- Design, development, implementation and testing of interoperable Galileo/GPS/EGNOS prototype receivers.
- Generation of European competence in GNSS receiver technology by initiating R&D activities leading to cooperation between industry, research organisations and universities.
- Pursue the effort generated in FP6 in preparing the Galileo market by introducing at an early stage Galileo technologies, especially in the mass market receiver area.
- Ensure a competitive advantage for European players in the area of Galileo receiver and core technologies.

Significant effort has been devoted in FP6 to R&D for mass market receiver technologies. The GRAMMAR project will consider and analyze these FP6 achievements and expand and explore on new features for special mass market segments.

The activities will be based on the inputs from the prototyping results of the GREAT project (of which GRAMMAR is a direct continuation) and focus on the development of:

- Multiple-frequency low power single chip GNSS radio front-end designed to address the challenge for a plurality of advanced mass-market applications.
- A baseband prototype implementing advanced features not currently seen in mass market receivers.
- Prototyping advanced algorithms in FPGA to determine their suitability for mass market receivers.
- Simulations addressing algorithms and techniques for receivers beyond the current state-of-the-art such as complexity reduced multipath mitigation, and non-line-of-sight detection and mitigation.
- Studying the suitability of inexpensive sensors and/or assistance from existing wireless networks for improved indoor and urban position solution robustness and availability.

Budget breakdown

The project is investing during its entire lifetime in the development of new concepts for future development of GNSS mass market receivers. The proof of concept of the key enabling technologies will require extensive simulations and hardware for the development of test-beds. This extensive research effort requires resources with different expertise from the industry, academic and research centers. As a total the industrial partner will commit an effort of 87.2 PM for the 24 months, whereas the academic will account for 115 PM and research centers will account for 84 PM.

The total project costs of approximately 2.6M are deemed necessary in order to carry out all the activities foreseen by the three project participants throughout the project duration. These costs include the person month costs of partners involved in the project RTD activities (based on the official person month rate of each participant). The costs cover the person months necessary to carry out all activities related to the technical, management and dissemination Work packages.

The requested EC grant to the overall project budget is compliant with maximum contributions by activity type as percentage of the respective costs and compliant with costs model applied to each participant (depending on the type of legal entity concerned and the accounting system).

Project duration

The project duration was 24 months as agreed in the Grant Agreement and started on February 1st 2009. Due to Amendment 1 of the Grant Agreement, the project was extended to 30 months duration.

Consortium overview and roles

To achieve the goal of the project, a consortium with a well-recognized background and specific competence has been put together. The consortium was constructed by taking into account that the resources are limited and that all partners must have a clear role that leads to good technical, exploitable results. The partners should not have only complementary skills in different fields addressed by the project, but also a clear business area orientation in the project.

The GRAMMAR project was addressing the development of GNSS mass market technologies by considering the achievements of previous FP6 activities and extending the current state-of-the-art of GNSS receivers exploring new and advanced features to pave the way for the on time commercialization of mass market receivers matched to a wide variety of market segments. Achieving the technical challenges addressed by GRAMMAR cannot be done without strong and multidisciplinary partners.

The partners have been selected with these key motivations in mind. The GRAMMAR consortium gathers the necessary skills to fulfill the high level requirements of the project and to design and implement forefront technologies to build innovative and efficient solutions. DLR is proud to lead a consortium comprised of key satellite navigation experts from around Europe, in order to address the call topic GALILEO-2007-3.1-01.

Ensuring a competitive advantage for European players in the area of Galileo/GNSS mass market receiver requires commitment from key manufacturers within Europe. To this extent, the GRAMMAR consortium which has been built up has strong experience on the background technologies that will be further researched and developed in the framework of the project. The GRAMMAR consortium draws on a powerful combination of:

- Algorithms from a leading space science research team with extensive experience in international technical projects especially within European Research Framework Programmes (DLR)
- Radio design from a RF company highly skilled in satellite and MMIC systems design, test and integration (ACORDE)
- Baseband design and development, and algorithm enhancements from a leading technical university (TUT)

The project work plan ensures that the competences are brought together in a synergic manner so that all converge to the common objectives of the GRAMMAR project. Some of these competences were already used in the past and are still used in present projects. The design flow and inter-working procedures between all the partners have been successfully established and worked together to the overall success of the past objectives in the FP6 GREAT project, whose results have been already made available to the GSA.

Project Results:

GRAMMAR represents a highly innovative approach to developing a prototype GNSS receiver, targeted at mass market applications, with the widest potential exploitation. The goals of GRAMMAR's technical work are:

- The development of a hardware prototype for a mass market receiver using a single chip dual frequency radio front-end and an FPGA based baseband allowing for rapid prototyping of advanced algorithms and techniques.
- The identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers.

Given these goals GRAMMAR has achieved the following results and innovations:

GRAMMAR has studied the state-of-the-art in present GNSS technologies for mass market applications, market growth expectations, and future technologies that could be applied in a short to medium term with focus on receiver architectures and algorithms. GRAMMAR also covered the limitations of the technologies currently used for these applications and researched those that will be required in a near future. We identified the needs surrounding a particular kind of mass-market GNSS receiver, environment scenarios, usability and general performance goals. Thus, it was possible to set more specific targets for the receiver development. A notable obstacle found during this stage was that despite the current maturity of GNSS receivers, there was a considerable lack of publicly accessible literature on receiver requirements. For this reason the consortium carried out their own research in many topics not just for the requirement results but for the methodology itself, in order to be able to get such results. This original research was demonstrated in several publications, different studies showing calculation methods for GNSS receiver requirements such as analog bandwidth or phase noise.

Furthermore, initial integration between the front-end developed during the GREAT project and the preliminary baseband design was performed. Even though the result was not fully successful, it provided a valuable insight about the methodology to be followed for the remaining integration tasks during the project. Several parallel strategies for integration tests were devised, in particular the development of additional radio front-ends using commercial components to allow a more reliable test schedule, as well as versions with USB interfaces to ease software analysis.

The development of the radio front-end was twofold. On the one hand, an MMIC design based on the front-end from the GREAT project was carried out, while on the other hand, several other versions based on commercial components were implemented for simplifying the baseband platform testing as a back-up solution and for demonstrating future products and services from ACORDE. The MMIC development was planned in two foundry runs. The first one would be an evolved version of GREAT with a higher degree of integration and flexibility, while the second one would be the final implementation of a dual-band receiver. Two main problems affected the first GRAMMAR version making the first prototype unusable for testing. The second version was a considerably more advanced MMIC. It underwent a severe power reduction process with a deep optimization of most of the front-end stages, and a new low-power image-rejection filter was implemented. This time the results were very promising, with very good performance in most of the subcircuits, but again two problems (L1 channel could not tune in band due to deficiencies in tolerances, noise figure 10dB greater than planned) did not allow the direct use of the MMIC in an integrated platform. Hence, a support prototype was built using external LNAs and a frequency correction stage for L1 to try to have a working platform for the FPGA using GRAMMAR's MMICs. Further, a third version was designed, correcting the faults of the previous one to have a functional prototype at least shortly after the project end demonstrating ACORDE's commitment with the project goals and conviction in this R&D path. The integration process has been slow despite the use of commercial components for the test boards. Part of these delays have been due to faults in the prototypes and physical/electrical problems that were not apparent until the actual integration started taking place.

The main problems encountered during the implementation of the baseband were related to integration of radio front-ends with the baseband hardware, dual-frequency tracking and implementation of Galileo data decoding. TUT has implemented a dual-frequency dual-system GPS L1/L5 Galileo E1/E5a receiver baseband processing unit in the form of a flexible, hardware accelerated software. This implementation is called TUTGNSS. It also includes a data monitoring tool that allows visibility of raw data streams along the critical points of the chain, thus making the troubleshooting and testing process very straightforward.

Currently, the debugging and testing of the commercial-of-the-shelf (COTS) L1/E1 and L5/E5a RF front-ends integrated with the TUTGNSS on a COTS FPGA is ongoing to solve any remaining issues and demonstrate the GRAMMAR goal of a functional hardware prototype for a mass market receiver using dual frequency radio front-ends and an FPGA based baseband allowing for rapid prototyping of advanced algorithms and techniques.

Enhanced algorithms in the baseband and for hybrid data fusion using INS, WLAN, and LTE as planned in the proposal have been researched and investigated. Testing of the algorithms has been done by simulations using for instance the newly developed channel model for joint positioning and navigation of GNSS and LTE. Besides that an LTE/OFDM based test-bed and a prototype receiver with advanced baseband processing algorithms have been implemented and first measurements have been conducted. The feasibility of complexity reduced multipath mitigation in an FPGA has been studied. The BFC ionospheric correction algorithm was implemented in the prototype GNSS receiver in WP2. The research results in WP3 have resulted in two patent applications and more than 50 publications in journals and conferences. Thus, the identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers has been achieved.

As result of the technical work carried out in GRAMMAR, two patent applications have been submitted and another two are under preparation. Further, IPR such as the open-source TUT Simulink Galileo E1 signal simulator, the TUTGNSS design, the channel model for joint positioning and navigation of GNSS and LTE, and the 3GPP-LTE positioning platform, will be exploited by the partners through licensing and participation in new projects, which use these platforms. ACORDE, as an SME, has created a specific heavily GNSS-oriented division within the company with its own business plan. Among others, ACORDE will commercially exploit an L1 and L5 radio front-end with USB interface for SDR GNSS receivers, MMICs (both as IP and as a demonstration of their design capabilities), and multi-frequency front-ends. Apart from that, ACORDE will also use the IPR generated within GRAMMAR in future FP7 projects.

GRAMMAR published more than 50 technical and scientific contributions in journals, magazines, conference proceedings and books. Moreover, GRAMMAR has been presented at eight conferences and workshops in Europe and the USA. The work and results of the GRAMMAR project were presented to international experts at the GRAMMAR final workshop held during the first

International Conference on Localization and GNSS (ICL-GNSS) 2011 in Tampere, Finland, June 29/30 2011. Through ICL-GNSS and the book "GALILEO Positioning Technology", GRAMMAR has achieved a long lasting impact in the scientific and technical community.

Concerning future work in the domain of the project, the following three research topics should be addressed by developing an enhanced mass market navigation receiver using Galileo and EGNOS:

- Multi-sensor navigation with tightly integrated sensors to develop low-cost and low-power navigation devices for instance as systems-on-chip (SOC) or systems-in-package (SIP),
- Indoor navigation to close the location based service gap experienced today by mobile phone users,
- Highly integrated multi-frequency professional/PRS receivers for all GNSS frequency bands to decrease costs and to increase customer base for professional/PRS services.

WP1 Market, Commerical and Exploitation

One of the first steps carried out in GRAMMAR was a study the state-of-the-art in present GNSS technologies for mass market applications, market growth expectations, and future technologies that could be applied in a short to medium term with focus on receiver architectures and algorithms. The identification of these commercial needs and technological challenges was presented in the document D1.1 Market Definition and Core Technology Report, which served not only as a basis to set specific goals for the project, but also to provide to the consortium members a better understanding of the field of GNSS from a mass market perspective, setting objectives of potential interest for future market-oriented research and ideas for commercial exploitation of products and services. D1.4 Gap Analysis of GNSS Receivers and Technology covered the limitations of the technologies currently used for these applications and those that will be required in a near future. Part of this work encouraged the creation of a specifically GNSS-oriented division within ACORDE for these future activities.

The outputs of this study served as a starting point for the requirements and specifications of the receiver to be developed for GRAMMAR. Once, we identified the needs surrounding a particular kind of mass-market GNSS receiver, environment scenarios, usability and general performance goals, it was possible to set more specific targets for the receiver development. One notable obstacle found during this stage was that despite the current maturity of GNSS receivers, even if for the first generation of public signals, there was a considerable lack of publicly accessible literature on receiver requirements. For this reason the consortium had to carry out their own research in many topics not just for the requirement results but for the methodology itself, in order to be able to get such results. For instance, GRAMMAR conducted a mass market navigation receiver survey. The questionnaire responses suggested that the cellular handset market is the key for the GNSS Mass Market and the adoption of advanced receiver technologies is appropriate to this market only if there is no negative impact on cost. The aforementioned original research was demonstrated in several publications, different studies showing calculation methods for GNSS receiver requirements such as analog bandwidth or phase noise.

Part of this work package was the initial effort for an initial integration between the front-end developed during the GREAT project and the preliminary baseband design already owned by TUT.

Even though the result was not fully successful due to practical limitations, it provided a valuable insight about the methodology to be followed for the integration tasks for the rest of the duration of the project. Several parallel strategies for integration tests were devised, in particular the development of additional radio front-ends using commercial components to allow a more reliable test schedule, as well as versions with USB interfaces to ease software analysis. Other, more technical, conclusions were reached regarding the practical limitations of the interfaces used, like mechanical and electrical reliability (e.g., SPI was found particularly sensitive for communication between PCBs that demanded additional precautions from the board designer's perspective).

Another main part of this work package was the technology exploitation. As result of the technical work carried out in WP2 and WP3, two patent applications have been submitted and another two are under preparation. Further, IPR such as the open-source TUT Simulink Galileo E1 signal simulator, the TUTGNSS design (see next section), the channel model for joint positioning and navigation of GNSS and LTE, and the 3GPP-LTE positioning platform, will be exploited by the partners through licensing and participation in new projects, which use these platforms. ACORDE, as an SME, has created a specific heavily GNSS-oriented division within the company with its own business plan. Among others, ACORDE will commercially exploit an L1 and L5 radio front-end with USB interface for SDR GNSS receivers, MMICs (both as IP and as a demonstration of their design capabilities), and multi-frequency front-ends. Apart from that, ACORDE will also use the IPR generated within GRAMMAR in future FP7 projects.

To conclude, this work package has achieved all of its objectives, e.g., requirements capture, technical specifications, market segment definition, and the business and exploitation plan, except for the integration of the GREAT RF front-end with the TUTGNSS baseband.

For future similar projects, access to the requirements capture and possibly specification of previous projects would be very beneficial.

WP2 Advanced Hardware

The purpose of this work package was the development of a GNSS receiver demonstration platform that would show architectural and technological progress that could be directly applied to mass-market receivers even though it would not be directly a mass-market receiver prototype. ACORDE would implement the radio front-end, original MMIC designs, while TUT would design the baseband processing, part in digital circuitry running on an FPGA, and part on software.

The development of the radio front-end was twofold. On the one hand, an MMIC design based on the front-end from the GREAT project was carried out, while on the other hand, several other versions based on commercial components were implemented, with the intention of both easing the testing of the baseband platform, serving as a back-up solution, and serving as a demonstration for future products and services from ACORDE.

The MMIC development was planned in two foundry runs. The first one would be an evolved version of GREAT with a higher degree of integration and flexibility, while the second one would be the final implementation of a dual-band receiver. Two main problems affected the first GRAMMAR version, greatly reducing the error margin for the second one. A fault in the digital blocks of the design made it impossible for the PLL to lock, while the bias circuitry that provided current/voltage references to most of the analog blocks did not work as simulated, showing the limitations of the tolerance models.

This made the first prototype unusable for testing purposes, even though it still provided useful information for the remaining development.

The second version was a considerably more advanced MMIC. It underwent a severe power reduction process with a deep optimization of most of the front-end stages, and a new low-power image-rejection filter was implemented. This time the results were very promising, with very good performance in most of the subcircuits, but again two practical problems arose, not allowing the direct use of the MMIC in an integrated platform. First, one of the local oscillators did not match simulation expectations. Its oscillation frequency went far beyond the limits set by simulation models, indicating more deficiencies in the tolerance estimation of the technology. This made the L1 channel unable to tune in the band. Secondly, the noise sources of one of the analog subcircuits were largely underestimated when convergence problems in the simulation during the optimization process went unnoticed. This made the overall noise figure of the front-end more than 10dB greater than planned.

The results of the second MMIC run led to two decisions. Firstly, a support prototype would be built using external LNAs and a frequency correction stage for L1 to try to have a working platform for the FPGA using GRAMMAR's MMICs. And secondly, a third version would be designed, correcting the faults of the previous one hoping to have a functional prototype if not within the official duration of the project, at least shortly after, to demonstrate ACORDE's commitment with the project goals and conviction in this R&D path. Due to schedule priorities and delays in the global planification it has not been possible to test the FPGA with the second version of the MMICs. However, ACORDE is currently independently working on the preparation of the testing of the third version to provide additional documentation with the results of this new design. The new design was modified to be more robust in a technology with a good cost-performance ratio (as demonstrated in the performance expectations, comparable to other front-ends implemented in more expensive processes) but not particularly well modelled.

The integration process has been slow despite the use of commercial components for the test boards. Part of these delays have been due to faults in the prototypes, most likely caused during the testing process and handling of the boards, as the experiments pose mechanical and electrical stress, which could not be fixed in location and required them to be sent back to ACORDE for repairs. This could have been minimized if other test strategies had been followed, like having another version of the FPGA development platform at ACORDE to run TUT's cores, but it was not thought necessary in the project plan until past the point where it was no longer worth considering. Other delays were caused by physical/electrical problems that were not apparent until the actual integration started taking place, showing specifications that had to be reviewed or directly were not considered from the beginning and had to be added.

COTS-based platforms proved to be extremely useful not just for testing that would both serve as a backup solution and help the design of the MMICs, but also as a starting point for future applications and services. Having USB versions for software analysis has been demonstrated to be a particularly powerful tool as well.

In the following, we describe the work related to the design and implementation of the GNSS receiver's baseband processing unit developed at TUT (TUTGNSS). TUTGNSS is a dual-frequency dual-system GPS/Galileo baseband and navigation processor. Hardware for supporting all signals of interest; Galileo E1/E5a and GPS L1/L5 has been designed and implemented. The most significant feature in hardware is that only one type of tracking channels is used. This "flexible tracking channel" enables a flexible usage of signals. Only BOC(1,1) modulation for Galileo E1 is implemented due the narrow bandwidth of selected radios. Galileo E1 memory codes are implemented. The remarkable finding here is that in big picture the memory usage of Galileo codes is negligible compared to other blocks of the system. Hardware support for pilot tone is implemented. Total hardware consumes 57.3 % of the total device resources. Thus, in future revisions the amount of tracking channels can be even increased. Currently, TUTGNSS has 16 tracking channels. The VHDL description is over 19K lines long. The software part has been designed and implemented and consists of over 5K lines of C code. In addition to the baseband processing, TUTGNSS also has an inbuilt data monitoring tool which allows gathering sampled data streams at different stages of the baseband processing chain. This capability enables an easy and efficient debugging and location of anomalies in the data processing. This tool uses Telnet and Ethernet protocols to transfer very high speed data from the FPGA to a PC, which can be later processed or plotted using MATLAB. In the absence of sophisticated test simulators or unavailability of real signals from satellites in the sky, this data monitoring tool comes in very handy to test the performance of the device under implementation.

The main problems encountered during the implementation of TUTGNSS were related to integration of radio front-ends with the baseband hardware, dual-frequency tracking and implementation of Galileo data decoding. Issues with the radio front-end were identified using the aforementioned data capture tool. The actual issue and its solution have been described in the earlier paragraphs. With regards to dual-frequency implementation, TUTGNSS employs an assisted-initiation-of-tracking mechanism for the GPS L5 and Galileo E5a signals. Specifically the corresponding L1 and E1 signals of the visible satellites are first acquired and tracked. On successful tracking of these signals, the direct tracking of L5 and E5a signals of these satellites is initiated using Doppler and code delay information from the L1 signals. However, this was difficult to achieve initially due to the lack of visibility of the signals in the internals of the baseband processing unit. The implemented data capture tool went a long way in aiding this mechanism. During the implementation of the Galileo data decoder, the main challenge was related to the interpretation of Galileo data structure as mentioned in the Interface Control Document. A couple of inconsistencies in the document were reported back to EC during the final review.

To conclude, TUT has implemented a dual-frequency dual-system GPS L1/L5 Galileo E1/E5a receiver baseband processing unit in the form of a flexible, hardware accelerated software. This implementation is called TUTGNSS. It also includes a data monitoring tool that allows visibility of raw data streams along the critical points of the chain, thus making the troubleshooting and testing process very straightforward.

Concerning future projects, it is important to start early with integration efforts of different hardware parts and have fall back solutions based on more conservative designs available early in the projects. The required testing facilities and capabilities of the partners need to be assessed and reported early in the project and a testing plan needs to be developed to ensure that testing is not limited, e.g., by the unavailability of test equipment. Further, all partners involved in hardware development should participate in integration and test meetings to allow faster solutions of any integration problems.

WP3 Enhanced Algorithms

This section summarizes the work related to enhanced baseband receiver algorithms for Galileo-based positioning, with and without additional aiding (cellular/LTE-based, sensor-based and WLAN-based). The work has been carried out in four sub-work packages in WP3.

In work package 3100 Prototyping design, implementation, and evaluation the following achievements have been accomplished:

- The complexity reduced multipath mitigation (CRMM) algorithms have been analyzed in VHDL and the viability of CRMM in VHDL has been shown. For example, up to 4 dual-channel receivers use 29% of the FPGA resources. In this case, we employ 51 correlators for each of the 2 channels for I/Q and for each of the 2 channels for pilot/data, i.e., in total 204 correlators for one satellite. This figure can be further decreased by using less correlators or tracking only the pilot signals.

- An advanced LTE test-bed has been developed and implemented. Four base station transmitters realized with 2 FPGA boards generate OFDM-modulated signals. The receiver is a software receiver, integrating a commercial-of-the-shelf (COTS) 2.4 GHz front-end, an FPGA based data grabber and workstation. The workstation allows real-time processing of captured data with acquisition and synchronization algorithms to measure time difference of arrivals (TDOAs) between the base stations.

In work package 3200 Receiver baseband algorithm design, simulation, test, and validation the following achievements have been accomplished:

- It was shown that unambiguous acquisition approaches bring no benefit in the presence of severe bandwidth limitations as those used in mass-market Gallileo receivers (e.g., below 4 MHz double-sided bandwidth). Thus, the unambiguous acquisition is beneficial only for wide receiver bandwidths. Two new methods regarding the acquisition have also been introduced: a method that removes the sub-carrier before the correlation part (DUAL method) and a subspace-based coherent acquisition method that is insensitive to data bit transitions. The main points here are , that the sub-carrier removal before correlation can decrease to a certain extent the complexity of the acquisition stage, and that the coherent subspace-based approaches offer up to 1 dB better acquisition performance than the incoherent ones while requiring only one half of the correlators used by differentially-coherent or incoherent symbol averaging.

- The main multipath mitigation solutions developed within GRAMMAR are BASE (low complexity multipath mitigation), CRMM (complexity reduced maximum likelihood multipath mitigation), and subspace tracking with unitary ESPRIT. BASE performance shows a good trade-off between algorithm complexity and benefits in multipath environments with respect to other multipath mitigation algorithms. The subspace tracking with unitary ESPRIT yields performance gains of 12 m for E5a at C/N0 = 56 dB-Hz and 120 m for E1 signals at C/N0 = 49 dB-Hz. Also a C/N0 estimator is presented that can be used to enhance the tracking stage estimation in a two-stage tracking structure that achieves the performance of HRC, but without the loss-of-lock problem of HRC.

- Concerning ionospheric corrections, we demonstrated that dual frequency receivers can mitigate the ionospheric errors in the absence of other error sources (such as multipaths) and that they also preserve their advantage over the E1 single frequency receiver in multipath environments. It is also shown that the Brute Force Constraint (BFC) ionospheric correction algorithm, developed within GRAMMAR, typically gives the best results (as a tradeoff complexity/performance) among the other two tested dual-frequency ionospheric correction algorithms in the presence of pseudorange errors due to multipaths.

- Wideband and narrowband interference has been analyzed in the context of Galileo signals. The results in the presence of wideband interference indicate that this is not a major threat in Galileo receivers. The narrowband interference, however, can be to a certain extent mitigated by using a dual-frequency receiver approach, which was demonstrated through some performance examples.

- We also applied advanced receiver positioning algorithms to OFDM based communication systems. For instance, we applied the CRMM based on Slepian's functions to OFDM based communication systems. Slepian's function yield an approach for the efficient intercarrier interference (ICI) mitigation in OFDM based communication systems. Simulation results demonstrate that for multipath channels, the new ICI mitigation algorithms can reduce the uncoded bit-error rate by more than an order of magnitude compared to classical ICI mitigation algorithms over a wide range of maximum Doppler frequencies.

- New initial acquisition algorithms with implicit interference cancelation techniques were developed to mitigate LTE base station interference due to an intended frequency re-use of 1. The proposed algorithms enable us to improve the TDoA estimation accuracy at cell boundaries as well as to improve the detection probability for initial acquisition at cell cores.

In work package 3300 HDF algorithm design, simulation, test, and validation the following achievements have been accomplished:

- Regarding the sensors part, a gyro-based positioning cart was built within GRAMMAR to provide accurate, cm-level accuracy indoors, as a reference point for algorithm testing.

- WLAN has been studied extensively, with the main focus on HDF of WLAN with Pedestrian Dead Reckoning (PDR) data, using various filters (EKF, PF and map information). The filtered WLAN positioning solution is about 4 times better than the unfiltered one. Also, when combining WLAN with PDR, the best results are obtained with the Complementary Extended Kalman Filtering (CEKF). However, the particle filters are more suitable to be used with map information data, in order to enhance the location solution.

- The fusion of GNSS with LTE including NLOS detection and mitigation has been researched and implemented. We show the improvement in using LTE in critical scenarios to obtain a better position fix.

In work package 3400 Algorithms Integration, Test and Report the following achievements have been accomplished:

- A common platform based on Simulink and the channel model for joint positioning and navigation of GNSS and LTE has been used in the tests/simulations. The channel model has been develop in WP 3100 and WP3400 based on WINNERII and DLR's LMS channel models.

- Simulation results are first shown for GNSS (tracking and ionospheric corrections), then for 3GPE-LTE test-bed and integration results.
- It is shown that some performance enhancements in terms of reduced RMSE error and loss of lock can be achieved in the tracking stage when using advanced multipath mitigation algorithms, such as BASE compared to the classical narrow correlator.
- Additionally, we show the fusion of LTE and GNSS in the combined channel model by an extended Kalman filter. Especially in critical scenarios such as urban canyons, where to few satellites are visible or the TOA measurements have large errors due to multipath and NLOS propagation the fusion of LTE and GNSS can mitigate large errors.
- We also discuss some of the bad channel conditions from the point of view of ionospheric corrections, when multipath errors are more significant than the ionospheric errors.
- It is also shown that the delay error distribution in realistic urban channel environments typically obeys a Gaussian distribution, and that E1 signal has typically higher delay estimation errors than E5a.
- Concerning the 3GPP-LTE test-bed, we investigated the effects of sampling clock offset (SCO) and carrier frequency offset (CFO) with respect to initial acquisition and correlation based detection for TDoA estimation. First measurements with DLR's channel sounder using the same system bandwidth of 20 MHz and the SAGE algorithm for multipath component resolution showed a TDoA error between 1.5m and 9m for an indoor femto-cell setup. These values can be used as rough expected error bound for the LTE test-bed and for error modelling in the hybrid data fusion (HDF) framework. Our first results from the LTE test-bed revealed new challenges for implementation, which where yet not seen in simulation, e.g., the distortion of the narrowband primary synchronization signals due to the RF front-end prohibits their usage for accurate timing synchronization.

The main problem in WP3 that has been encountered during the course of the project was the unavailability of the prototype GNSS receiver from WP2. Hence, we could not capture any data for GNSS to test the advanced algorithms with realistic data. As fall back solution, we used the channel model for joint positioning and navigation of GNSS and LTE for testing and simulations to investigate several algorithms under realistic conditions. Furthermore, only the BFC ionospheric correction algorithm was prototyped and implemented in WP2 due to the problems with the prototype GNSS receiver in WP2.

To conclude, the algorithms in the baseband and for hybrid data fusion using INS, WLAN, and LTE as planned in the proposal have been researched and investigated. Testing of the algorithms has been done by simulations using for instance the newly developed channel model for joint positioning and navigation of GNSS and LTE. Besides that an LTE/OFDM based test-bed and a prototype receiver with advanced baseband processing algorithms have been implemented and first measurements have been conducted. The feasibility of complexity reduced multipath mitigation in an FPGA has been studied. The BFC ionospheric correction algorithm was implemented in the prototype GNSS receiver in WP2. The research results in WP3 have resulted in two patent applications and more than 50 publications in journals and conferences.

Concerning the work among partners, it was good to have a combined channel model as fall back to captured data from hardware for testing the enhanced algorithms. Further, as a lot of work was completed in the form of publications it would be beneficial to write summary deliverables with the detailed work contained in the appended publications. This would reduce overhead work for research oriented work packages in future projects.

WP4 Presentation and Dissemination

GRAMMAR has successfully published six journal papers, with three more awaiting approval, 42 conference papers, with four more awaiting approval, two book chapters, with two more books under preparation, eight M.Sc. theses, and three Ph.D. theses submitted during the entire duration of the project. These results have been achieved by allocating the majority of resources to the technical work in WP2 and WP3. Among the books under preparation, the GRAMMAR team initiated the book "GALILEO Positioning Technology", which is currently under writing, to achieve a long lasting impact of the project in academia and industry. Additionally, the GRAMMAR project has been presented at eight conferences and workshops in Europe and the USA including the ICT Mobile Summit 09, 10 -12 June 2009, Santander, Spain, the Galileo Application Days, 3-5 March 2010, Brussels, Belgium, and the NASA Project Management Challenge, Feb 9-10 2011, Long Beach, CA, USA.

The GRAMMAR final workshop was held during the first International Conference on Localization and GNSS (ICL-GNSS) 2011 in Tampere, Finland, June 29/30 2011. The project team presented an overview on the work executed and its latest results to a total 44 participants external to the project. The participants came from 16 countries including Argentina, Australia, and USA. Besides the GRAMMAR project also other EU FP7 projects such as GAMMA-A attended the GRAMMAR final workshop and participated in the ICL-GNSS 2011. Note, ICL-GNSS was inaugurated by GRAMMAR and will be a regular annual scientific conference. It is planned that ICL-GNSS 2012 will be held in Munich, Germany and ICL-GNSS 2013 in Turin, Italy. Thus, GRAMMAR has achieved a long lasting impact in the scientific and technical community beyond the project duration.

No main problems were encountered in WP4.

To conclude, thanks to the excellent work in WP1, WP2, and WP3, GRAMMAR could publish more than 50 technical and scientific contributions in journals, magazines, conference proceedings and books. Moreover, GRAMMAR has been presented at eight conferences and workshops in Europe and the USA. The work and results of the GRAMMAR project were presented to international experts at the GRAMMAR final workshop held during the first International Conference on Localization and GNSS (ICL-GNSS) 2011 in Tampere, Finland, June 29/30 2011. Through ICL-GNSS and the book "GALILEO Positioning Technology", GRAMMAR has achieved a long lasting impact in the scientific and technical community.

The collocation of the final project workshop with an international conference is an excellent means to reach a larger audience also from countries outside Europe. The Galileo Application Days was a great event to present the project, network with other projects and inform experts and non-experts on the project work. In the view of GRAMMAR, it would be very beneficial if EC could organize such an event annual or biannual. Moreover, such an event would be very suitable for collocating project workshops.

Potential Impact:

Develop competences in the domain of the project within the EU

In the following, we list main competences developed by the participants from GRAMMAR project activities:

- Gained experience in software development: Open-source Simulink Galileo transmitter-receiver unit has been provided for the general public (in order to facilitate the R&D in the Galileo signal processing field)
- MSc and PhD students have graduated in the research field of the project and they are now prepared to embark on GNSS-related careers
- Knowledge on dual-frequency multi-system GNSS receiver design (RF, baseband hardware, PVT software)
- Knowledge on complementary indoor positioning methods such as WLAN and inertial sensors
- Knowledge on algorithms for baseband algorithms (acquisition, tracking, ionospheric correction, interference mitigation, multipath mitigation, NLOS detection and mitigation, etc.) and hybrid data fusion algorithms of GNSS with INS, WLAN, and 3GPP-LTE.
- Gained experience on system engineering of complex prototypes: concept development (hardware and software design partitioning, e.g., in TUTGNSS and LTE based positioning platform, procurement and build-up of hardware, adaptation, implementation and integration of software with respect to hardware constraints, verification and testing of complete prototype
- Gained experience in development, implementation and testing of hardware prototypes: FPGA based baseband implementation of algorithms for GNSS and LTE/OFDM test-bed; RF front-end development/procurement for GNSS and LTE/OFDM
- Efficient use of collaboration tools such as team-site and web conference tool, e.g., for writing joint documents and sharing documents as discussion basis during telephone conferences
- Project management best practices suitable for EU-FP7 projects ,e.g., templates for deliverables, regular telephone conferences and meetings, documentation of minutes and reporting
- Organization of tutorials, workshops and conferences for disseminating project results to a wider engineering audience.

Progress beyond the state-of-the-art

In the sequel, we describe innovations and relevant progress with respect to the state-of-the-art prior to the GRAMMAR project"

- Dual-frequency dual-system L1/E1/L5/E5a receiver baseband and position calculation
- Low power dual-channel dual-frequency radio front-end integrated in a single chip in a comparatively low cost technology (CMOS 0.18um)
- Study of fractal antennas, BAW and MEM technologies for L1/E1/L5/E5a in highly integrated applications
- Study of vector DLL for mitigating short-term blockage/attenuation of GNSS signals
- The optimal bandwidth for E1 and E5a mass-market Galileo receivers has been derived according to joint optimality criteria (3 MHz double sideband in E1 case and 13 MHz in E5a case)
- Multipath mitigation algorithms optimized and adapted to Galileo E1 waveforms have been proposed (BASE/CRMM/optimized MGD)
- With respect to complexity reduced multipath mitigation (CRMM), innovations (see four publications and one patent application) have been achieved on "A Design Study on Complexity Reduced Multipath Mitigation" to show that CRMM can be implemented in VHDL with a correlator and channel structure proposed in WP3, "Analytical Optimized Complexity Reduction for Maximum Likelihood Position Estimation in Spread Spectrum Navigation Receivers" providing an improved and less complex method to compute the correlator banks used in CRMM, and "Low Complexity High Resolution Maximum Likelihood Channel Estimation in Spread Spectrum Navigation Systems" as well as "Time-Variant Maximum Likelihood Channel Estimation in Mobile Radio Navigation Systems" presenting time-variant CRMM based on Slepian's subspaces.
- Concerning acquisition and tracking through subspace methods based on MUSIC and ESPRIT algorithms, innovations (see three publications) have been achieved on "Coherent DS-CDMA Acquisition in Time-Variant Channels at Low Signal to Noise Ratios", "Decoupled Delay and Doppler Acquisition in DS-CDMA Systems at Low Signal to Noise Ratios", and "Low Complexity High Resolution Joint Timing and Doppler Acquisition for DS-CDMA Systems" providing higher accuracy than conventional acquisition methods by exploiting multipaths while keeping the complexity similar to the conventional methods.
- For computing the mean time to lose lock (MTLL), innovations (see two publications) have been achieved on "Analytical Computation of Mean Time to Lose Lock for Langevin Delay-Locked Loops" and "A Novel Tracking Jitter Computation Algorithm for Delay-Locked Loops in Spread-Spectrum Systems" to allow a faster and more accurate numerical computation of the MTLL than conventional methods.
- Concerning NLOS detection and mitigation, innovations (see three publications) have been achieved on "Analytical derivation of the False Alarm Probability and Detection Probability for GNSS NLOS Detection using a Dual Frequency Receiver", "Analytical Derivation of the False Alarm and Detection Probability for NLOS Detection" and "NLOS detection and mitigation based on confidence metric and EKF" to improve GNSS positioning for instance in urban canyons.

- The impact of multipath errors on the dual-frequency ionospheric corrections has been analyzed for the first time in detail, under both simplified and realistic channel conditions
- Study of WLAN indoor positioning based on fingerprinting
- Study of inertial sensors for indoor positioning
- Filtered WLAN positioning solutions have been proposed in order to aid the Galileo-based location, with significant increase of performance over existing WLAN-based solutions
- For communication systems, innovations (see seven publications and one patent application) have been achieved on "Hybrid data fusion and tracking for positioning with GNSS and 3GPP-LTE", "Data-Aided Location Estimation in Cellular OFDM Communications Systems", "On the benefit of location and channel state information for synchronization in 3GPP-LTE", "Efficient Intercarrier Interference Mitigation for Pilot-Aided Channel Estimation in OFDM Mobile Systems", "False Alarm and Detection Probability for NLOS Detection in LTE environments", "TDoA Subsample Delay Estimator with Multiple Access Interference Mitigation and Carrier Frequency Offset Compensation for OFDM based Systems", and "OFDM based TDoA Positioning Testbed with Interference Mitigation for Subsample Delay Estimation".

Develop user technologies to provide/improve the Galileo/EGNOS services

Here, we list developments leading to improve the Galileo/EGNOS service provision:

- Dual GPS/Galileo receiver for increased reliability and improved performance to encourage use of Galileo
- Advanced baseband algorithms such as acquisition and tracking methods that can compensate multipath and NLOS propagation in urban or indoor environments to improve positioning accuracy of GNSS navigation receivers
- Hybrid data fusion of GNSS with INS, WLAN and LTE to improve coverage and accuracy of positioning services based on Galileo services

Contribution to the adoption of the European GNSS

The GNSS receiver platform developed in GRAMMAR will be made accessible to the public with different degrees of availability to support user communities that either develop receivers for the European GNSS or need a receiver for the European GNSS. Production versions of the COTS-based radio front-ends will be commercially available by ACO for either independent baseband development or integration with the baseband processor developed by TUT. The prototyping hardware used for the implementation of the GNSS engine itself is a commercial model from Altera, so anyone with access to the FPGA core, the design and the software from TUT can easily integrate and use the GRAMMAR receiver by following its manual D2.12. It is also technically possible to adapt the receiver to other FPGA platforms by using different physical connectivity, depending on the conditions of use and/or modification of the IP in the licensing agreement.

In the following, we refer to the design and software from TUT for the FPGA as TUTGNSS design. It is possible to license out the TUTGNSS design. For TUTGNSS, it is possible to give out the basic GPS L1 under a BSD-like license for research and education use. TUT also advocates the use of the developed L1/E1/L5/E5a receiver for research and education use under similar conditions for the partners in other EC-funded receiver projects. For commercial exploitation, TUT is open for licensing out the technology under reasonable conditions.

Within GRAMMAR, TUT developed the open-source TUT Simulink Galileo E1 signal simulator. The simulator models a Galileo E1 baseband transmitter-channel-receiver chain. The TUT Simulink Galileo E1 signal simulator is an open source software allowing developers to test their baseband algorithms before implementing them in hardware. It is available through the following link: http://www.cs.tut.fi/tlt/pos/Software.htm.

TUT plans to use the experience and knowledge gained during the GRAMMAR project as part of new and existing MSc degree/course curriculums. A new Master's degree program majoring in Positioning and Navigation Technology has recently been initiated at TUT in the Department of Computer Systems. The scientific knowledge from the GRAMMAR project will be part of this curriculum. Simulink-based demos and exercises during lectures focusing on wireless positioning have been made and are planned to be made based on the open-source TUT Simulink Galileo E1 signal simulator and possibly E5a Simulink model built within GRAMMAR. This increases the awareness among the students regarding the European GNSS developments and potential. Such lectures have been held so far at TUT, Finland and UPB, Romania.

Participants of the GRAMMAR project have published more than 30 scientific and technical papers that present results on European GNSS in particular Galileo. GRAMMAR has participated in the Galileo Application Days 2010 and at the ICT Mobile Summit 2009 with project booths, organized the Tutorial "Challenges in Multi-System Multi-Frequency GNSS Receiver Design" at the SPACOMM 2010 and held its final workshop at the ICL-GNSS 2011.

The International Conference on Localization and GNSS (ICL-GNSS) was inaugurated by GRAMMAR and will be a regular annual scientific conference on wireless localization and GNSS including Galileo and EGNOS. The first ICL-GNSS 2011 was held in Tampere, Finland. It is planned that ICL-GNSS 2012 will be held in Munich, Germany and ICL-GNSS 2013 in Turin, Italy. Thus, GRAMMAR contributes through ICL-GNSS to the adoption of the European GNSS in the scientific and technical community beyond the project duration.

The GRAMMAR team initiated the book "GALILEO Positioning Technology". The book is currently under writing by known experts in the field of Galileo and EGNOS positioning technologies. The book will be published by Springer to foster adoption of European GNSS in academia and industry.

To inform project members and external stakeholders, such as chip manufacturers and integrators about the project results, dissemination and exploitation activities, GRAMMAR will use the GRAMMAR Project Alumni Group on LinkedIn (http://www.linkedin.com/groups?gid=4013779&trk=myg_ugrp_ovr). Members of the GRAMMAR project can use this Group to advertise activities and events relevant to GRAMMAR after the project end. All the stakeholders will be updated with the project achievements and outcomes through the GRAMMAR Project Alumni Group and the project website http://www.gsa-grammar.eu beyond the end of the project. Furthermore, the participants of the GRAMMAR project will use the group to stimulate discussion on mass market receiver topics to support the adoption of European GNSS

Support to standards development

In the GREAT project, of which GRAMMAR is a direct continuation, the final algorithm testing was performed with channel impulse responses from a ray tracing tool, which provided a coherent environment for joint GNSS and terrestrial cellular networks based navigation. However, one drawback of this approach was the lack of short term statistics of the channel, e.g., fast fading effects. Therefore, DLR has combined within GRAMMAR DLR's land mobile satellite (LMS) channel model and the WINNER II channel model to bring in the short term statistics. The outcome for GRAMMAR is a coherent testing environment for joint navigation with GNSS and cellular system, not only for long term statistics, e.g., GLoS bias information, the coherent scenarios parameters, and general large scale parameters, but also for short term statistics.

In discussions with industrial companies (Qualcomm and Nokia), it has been found that they still use the T1P1.5 channel model from GSM to evaluate the positioning performance in 3GPP-LTE. One reason for using the narrow band channel model for the wide band 3GPP-LTE system is the lack of modern channel models to incorporate information about the GLoS bias. This point is addressed by DLR's extension of the WINNER II channel model. Further, companies expressed their interest in simulating joint navigation of GNSS and LTE to estimate the performance of positioning services.

Hence, DLR will follow-up with relevant companies, e.g., Qualcomm and Nokia, to use the combined channel model for joint positioning and navigation of GNSS and LTE in the standardization of future releases of 3GPP's LTE and LTE-Advanced technologies.

Support to policy-making

The National Aeronautics and Space Administration (NASA) of the USA has been organizing annually the NASA Project Management (PM) Challenge, which is a NASA internal conference with more than 2000 participants designed to examine current program/project management trends, as well as provide a forum for knowledge sharing and exchange lessons learned. DLR, the German Aerospace Center, which is similar to NASA, is cooperating with NASA in the international track of the NASA PM Challenge. In addition to that, the GRAMMAR project was presenting the project and a case study on external unpredictable risk in the PM Perspectives track, which was a novelty. Thus, GRAMMAR raised the awareness about EU FP7 funded research and the European GNSS Galileo within NASA. Even, Mr. Bolden, the head of NASA, and Prof. Dr.-Ing. Wörner, the head of DLR, have been aware of this cooperation between NASA and DLR through the contribution of the GRAMMAR project.

Public benefits and contribution to social welfare

I-Cane (Intelligent cane) is a project that aims to develop a modular "intelligent" cane for blind people, equipped with integrated sensors and actuators to support blind people in navigation and obstacle avoidance. This high-tech cane might therefore include tactile feedback (e.g., the "tactile arrow" as designed by Monique de Wilt), GPS support, a talking compass, a 3-D camera and a host of other components. The GRAMMAR project had several discussions with Huub Grooten, the CEO of the I-Cane Foundation, and Richard Houben, chief scientist of the I-Cane project. Among others, we discussed possibilities to cooperate with I-Cane and gave technical advice to I-Cane on satellite navigation.

List of Websites:

http://www.gsa-grammar.eu

Dr. Stephan Sand,

Project Manager,

German Aerospace Center (DLR), Institute of Communications and Navigation, Oberpfaffenhofen, 82234 Wessling, Germany

Tel: +49 8153 281464

Fax: +49 8153 281871

E-mail: stephan.sand@dlr.de