Publishable Summary for 18NRM05 SupraEMI
Grid measurements of 2 kHz -150 kHz harmonics to support normative emission limits for mass-market electrical goods

Overview

The overall aim of this project is to develop new normative measurement techniques to enable regulation of interference caused by mass-market electrical products. The build-up of product emissions in the supraharmonic frequency range of 2-150 kHz, threatens to cause malfunction of other electrical products, power line communications, and critical infrastructure. Unlike other frequency ranges, the supraharmonic band has no effective regulation or normative measurement framework. This project will work with standards committees to develop a new measurement framework to facilitate the setting of realistic and credible supraharmonic interference limits and enable the regulation and compliance testing of mass-market goods.

Need

Mass-market electrical products emit interference into the grid conductors, which has been shown to cause malfunctions of other connected products, power line communications equipment and grid infrastructure. At frequencies below 2 kHz, this conducted harmonic interference has been regulated for some years by normative standards and associated compliance testing as part of the EMC (electromagnetic compatibility) directive. However, advances in electronics, and the growth of electric vehicle chargers and renewable energy, have led to increasing amount of interference at higher frequencies in the so-called “supraharmonic” range of 2-150 kHz. This interference is not regulated and its growth is now causing serious concern to utilities and product manufacturers. In 2017, this led to action from the standards community with the establishment of a working group (WG) of the Power Quality (PQ) community (International Electrotechnical Commission’s subcommittee: IEC SC77A) and the radio interference community (Comité International Spécial des Perturbations Radioélectriques: CISPR), to determine the gaps in the normative and regulatory requirements of the supraharmonic band.

One such gap is the lack of a rigorous, repeatable and acceptable measurement method, which is essential to establish a regulatory system for the supraharmonic range. To address this gap, IEC SC77A has convened an expert task force under WG9, to establish and publish a new normative method for the main PQ measurement standard IEC 61000-4-30. This WG9 has expressed their urgent need to develop a new metrological sound measurement method.

In order to develop emissions limits, compatibility levels must reflect the prevailing amount of interference that mass-market goods and grid equipment should operate without malfunction. Interference levels are presently defined taking only the laboratory testing environment into account. How well this assumption compares to real grid conditions and resulting behaviour of appliances must be confirmed. This requires measurements of real products using an artificial mains network (AMN) which will then be compared with measured emissions when the same products are connected in different electricity low voltage (LV) networks.

Emission testing of mass-market goods to ensure compliance against the limits will need to be done in the laboratory rather than the grid. This requires a realistic simulation of the grid which is achieved using an AMN. The AMN impedance characteristics are critical to ensure representative emission results. New grid impedance measurement data is needed to determine whether the AMN impedance characteristics are a realistic representation of the LV networks impedance over the full 2-150 kHz frequency range.

To enable supraharmonic regulation, there is a clear need to develop a measurement framework that must be robust, credible and acceptable to mass-market product manufacturers, PQ instrument manufactures, testing laboratories and grid utilities. The involvement of key WG conveners, a range of stakeholders and the close association of the project JRP Chief Stakeholder, is critical to smooth the path to timely new normative methods.

Objectives

The overall objective of the project is to develop a measurement framework for supraharmonics in the electricity network, such that realistic, credible and measurable procedures for compliance assessment can be incorporated into normative standards. The specific objectives of the project are:

1. To formulate a new normative method to measure supraharmonics (2 to 150 kHz) in electricity networks suitable for inclusion in the redefinition of IEC 61000-4-30 Edition 4, and which should be compatible with the method defined by CISPR 16, which is only appropriate for equipment emission measurements in laboratory. In addition, to implement the new method using suitable portable and traceable instrument(s) to measure voltage and current in the supraharmonic frequency range with accuracies of ≤ 1 %.
2. To validate the new method by conducting a laboratory comparison of the new method with the existing methods in IEC 61000-4-7 (2-9 kHz) and CISPR 16 (9-150 kHz) using the respective artificial mains networks (AMN) to represent the impedance of the electricity network, and examining emissions from a selection of electrical appliances.
3. To determine the suitability of supraharmonic compatibility levels (as defined in IEC 61000-2-2) by measuring the emissions from a selection of electrical appliances connected in a selection of LV networks. To use these on-site LV network measurements and to compare with the laboratory measurements to determine the suitability of the AMN approach as a realistic laboratory representation of LV network conditions.
4. To verify the applicability of the AMN characteristics by measuring network impedance characteristics of a number of typical LV electricity networks with a target uncertainty of 5 %. Measurements below 9 kHz will be used to verify the IEC 61000-4-7 AMN and measurements in the range 9 to 150 kHz will be used to verify the CISPR 16 AMN.
5. To contribute to the standards development work of the technical committees IEC SC77A WG 1, 8 and 9, and CISPR 16 by providing recommendations on improvements to supraharmonic measurement methods (4-30), and the normative specification for the AMN in-line impedances (4-7 and 2-2) as well as how these new methods should be applied to compare levels measured in the electricity network with supraharmonic compatibility levels (2-2), and ensure that the outputs of the projects are aligned with their needs, communicated to those developing the standards and to those who will use them, and in a form that can be incorporated into the standards at the earliest opportunity.

Progress beyond the state of the art

A new normative method to measure 2-150 kHz emissions in electricity network (Objective 1) and its laboratory comparison with the IEC 61000-4-7 and CISPR 16 method (Objective 2)

Developing a new emissions measurement method for IEC 61000-4-30 is not simply a case of extending the existing low frequency measurements. Whilst the metrology is reasonably well established below 2 kHz, multiple issues must be resolved related to the digital signal processing (DSP) algorithms and the practicality of a proposed solution for the supraharmonics frequency range. Emissions at these frequencies interact in a complex way dictated by the changing impedance of each appliance connected on the same supply. Many appliances have variable operational cycles and emissions change rapidly with time. Unfortunately, the traditional DSP methods do not deal well with fluctuating signals. Therefore, the core of this objective of the project will be to modify and develop a method that can accurately process emissions of this type. However any proposed solution must respect a traditional method defined by CISPR which is only useful for non-fluctuating signals. Furthermore, the 2-150 kHz range contains many resolvable frequency values, which if reported in the same way as for ≤ 2 kHz measurements, would result in 150 thousand results per second, which would be unmanageable for users. In addition, the new method must be highly efficient to compute as it must be implemented in real-time on existing instrumentation platforms. The new method will need to satisfy these conflicting issues and will build on the findings of the EMPIR project 17NRM02. These MeterEMI methods will need adaptation from the 20 kHz bandwidth fast edge signals of interest in that project, to the wider band modulated signals of interest in this project.

As the new method must respect the traditional CISPR 16 method, this must be demonstrated to gain acceptability by industry. The CISPR method looks at each frequency component in-turn, taking some time to sweep across the 2-150 kHz range, so that it can easily miss any fast-changing emissions. The new method should measure all frequencies at the same time, so that it is suitable for fluctuating emissions that better represent real life signals. The project will examine the differences between the CISPR and the new method, by making laboratory measurements on a collection of mass market appliances which are thought to give interesting emissions. The results will be an essential benchmark for industry to determine the difference between the methods.

Verify and improve the applicability of the AMN characteristics by electricity network emissions measurements (Objective 3) and direct electricity network impedance measurements (Objective 4)

Artificial mains networks attempt to simulate the impedance of the grid over a certain frequency range. This is important as appliance emissions, in the form of current, will only give rise to interfering voltage distortion if there is a finite source impedance. If the value of this artificial impedance is wrong compared to the grid at a given frequency, then the voltage emission will be wrong. At present, IEC 61000-4-7 defines an AMN for use in the range 2-9 kHz whilst the range 9-150 kHz is covered by a different impedance network, namely the AMN defined in CISPR 16. Furthermore, IEC 61000-4-7 considers differential mode measurements of phase-to-neutral signals, while CISPR 16 considers common mode measurements of phase-to-earth voltages. These AMN values were defined by historical impedance measurements, performed decades ago prior to the proliferation of mass-market power electronics, inverters and smart grid innovations. Some more recent work is published by IEC in the context of convertor connections.

Since it is unknown whether these AMN characteristics are representative of today's electricity networks, the project will use the same appliances as tested in the laboratory, to retest in a selection of three different LV networks (one for each) to determine cumulative emission levels and the suitability of the existing AMNs.

Following on from the laboratory measurements, the characteristics for a new normative AMN(s) will need to be determined. This will require direct measurements of the LV electricity network impedance for a range of different LV networks in order to define the AMN requirements that will represent typical LV networks.

The information will be verified and augmented by direct injection-based measurements of LV network impedance over the 2-150 kHz band in a variety of LV networks. This overview of network impedance characteristics will be used to propose updated AMNs to the relevant committees such as SC77A WG1 which will ensure future laboratory measurements are as realistic as possible. In addition, grid impedance measurements were developed in EMPIR SmartGrid2 (ENG52) using non-injection techniques. Whilst these techniques work at low frequency, they are not appropriate to the 2-150 kHz range due to the very low prevailing signal levels. Injection based measurements have been developed by TUD and EPV/EHU in university research projects and they will be further developed in this project.

Results

A new normative method to measure 2-150 kHz emissions in electricity network (Objective 1)

Initial work has been carried out to define the key metrics of the new method (such as accuracy, time resolution and frequency resolution). This process involved consultation with experts on IEC SC77A WG9 in meetings and using a questionnaire. An accuracy of ±10 % of the measured value was agreed over the full frequency range. In order to develop and select a method, a set of test conditions have been defined which include real-waveforms generated by common sources of higher frequency emission such as some photo-voltaic electronics and electric vehicle chargers. A number of published algorithms have been reviewed and implemented in simulation software for comparison, using the test waveforms. These algorithms include digital implementations of the following methods: CISPR-16, windowed Fourier, wavelet methods and compressive sensing. The performance comparison looked at the accuracy of these methods and computational performance as potential real-time solutions. The results were presented to IEC SC77A WG9 and a short list of methods has been selected for further investigation. The results were published in a peer-reviewed paper (see [4] at the end of the document).

For historical reasons and compatibility with other normative standards, WG9 must consider the use of digital CISPR-16 methods which group the measurements into a set of adjacent 200 Hz bands running across the 2 to 150 kHz range. In the traditional CISPR-16 analogue method, the output of each group is then applied to a so-called quasi peak detector, a peak detector and an average detector; digital versions of these historically analogue detectors will also need to be specified in the new standard. The CISPR-16 standard does not tightly define the implementation of the method and the accuracy specified as is +/-2 dB, which corresponds to -21/+26 %. As the method has many algorithmic parts that can be legitimately implemented in different ways, there are many degrees of freedom in a given implementation. To assess the range of possible results using all the possible compliant CISPR implementation, multiple implementations were made and tested, resulting in a variation in results of some ±40% with respect to the median value. This extent of variation shows that a reference digital implementation of CISPR 16 must be defined to meet the desired accuracy specification.

Another consideration with the digital CISPR method is that it requires a relatively high computational effort compared with more traditional power quality (PQ) algorithms such as the windowed Fourier method given in IEC61000-4-7. Mandating of the CISPR method may render some instrumentation platforms unsuitable for future power quality instrumentation. For this reason, it is proposed that a less computationally onerous Class S (statistical) version of method could be used to conduct the 24/7 statistical surveys, which are needed for grid PQ measurements. Such an algorithm would give conservative results compared to the grid disturbance limits used, such that if a test is passed with a Class S instrument, it will surely pass the more complex CISPR implementation, named Class A, which would more accurately represent the link with CISPR-16. The proposal is that this Class A instrument would be implemented using a well defined digital CISPR 16 implementation that has repeatability within the accuracy requirements of the method. Debate and decision on the proposals within the standards community is on going and it is possible that an entirely different approach may yet emerge. Recent work has concentrated on a simplified approximation to CISPR-16 for Class A, including and approximations to the quasi peak detector. Two drafted options for an annex to the 4-30 standard have been presented to WG9.

The project has also worked to develop novel algorithms. A review has been carried out on compressive sensing methods that have been reported in the literature and the project team has worked closely with authors of these methods to implement them. A novel method which is compatible with CISPR-16 based on a signal processing technique known as multi resolution analysis has also be developed within the project. This method is accurate to ±5%, is highly efficient and runs on a laptop computer in real-time as has been published in a peer-reviewed journal.

To validate the new method by conducting a laboratory comparison of the new method with the existing methods in IEC 61000-4-7 and CISPR 16 (Objective 2)

A commercial CISPR 16 receiver instrument has been obtained and has being tested and configured. A set of suitable domestic electrical appliances which are “candidates” to generate 2-150 kHz emissions have been obtained/procured. A test rig has been designed and built to test the appliances in the laboratory and is used together with some reference sampling equipment and transducers to transform the appliance working currents and voltages into the input of the sampling equipment. This equipment operates over the full 150 kHz frequency range and new calibration techniques have been developed for the transducers. The software for the sampling equipment has been designed to work in real time and will be used to implement various algorithms such as IEC61000-4-7 (to 150kHz) and CISPR16. The appliances have now been measured in the laboratory and the raw sampled waveform data captured. The results of a selected algorithm applied to this data so that the method can be compared with the commercial CISPR 16 receiver for each of the domestic electrical appliances in-turn. This will ensure that emissions measured in the laboratory are comparable with emissions measured in the grid. Such equivalence is directly dependant on how well the impedance of the grid is emulated in the laboratory and this is the subject of Objective 4.

To determine the suitability of supraharmonic compatibility levels (Objective 3)

No work is planned on this objective at this stage of the project. Determining the compatibility levels relies on the new method developed in response to Objective 1.

To verify the applicability of the AMN characteristics by measuring network impedance characteristics of a number of typical LV electricity networks with a target uncertainty of 5 % (Objective 4)

The impedance magnitude and phase frequency response of an AMN is currently being measured and the stability of the device addressed at a range of working temperatures. The AMN can be used to verify the performance of grid impedance measuring apparatus That will be used to determine the grid impedance at a number of locations.

To contribute to the standards development work of the technical committees IEC SC77A WG 1, 8 and 9, and CISPR 16 (Objective 5)

There has been substantial engagement with IEC SC77A WG9 regarding the next version of Power Quality measurements standard IEC61000-4-30 as detailed under Objective 1. Presentations were given to WG9 every 6 months since June 2019 including the latest meeting in September 2021. Several draft outline normative Annex for IEC61000-4-30 have been presented to WG9 with a number of options. Additionally, the conveners of IEC SC77A WG1 and WG8 and CLC SC205 are also being kept informed of the projects progress and joint briefings of WG9 and WG8 have been facilitated by the project team. These committees will make use of the new method (Objective 1) once it is has been agreed by WG9.

Impact

Two conference papers were presented to CPEM 2020 and five open-access articles has been published in peer-reviewed journals (see the list at the end of the document). An on-line mid-term workshop was held in November 2020 which was well received by the ~70 attendees, the presentations can be downloaded from the project web site. In addition, the stakeholder committee established by the project currently has 26 members. Regular contact via email has been maintained with the Chief stakeholder including attendance at the various meetings of IEC SC77A WG9 2020. The project website has been set up which is updated regularly with the latest progress and the project SharePoint is also in use. A tutorial workshop is planned for September 2021 at the CIRED conference.

Impact on industrial and other user communities

Experience has shown that imposing new regulations on large markets is fraught with political and commercial controversy. The multi-million market for electrical goods is highly competitive and small changes to product designs in order to comply with emissions limits can be hugely expensive to manufacturers in component costs and lost time to market for a new product; ultimately these costs are passed on to consumers. Yet without regulation, these same manufacturers, together with consumers, face the prospect of increased product malfunction and/or failure and/or faster product aging. In the longer term, regulation is in everybody's interest, but rigorous evidence will be needed to prove the case and primarily to agree levels at which product emission limits should be set. The measurement framework to be developed in this project has a key role to play in this; developing and applying it to determine the levels of emission in the power grid to which other appliances are exposed, is absolutely essential to the credibility and acceptability of new regulations and limits. The regulation of the emissions from mass-market goods should reverse the trend of increasing grid pollution and protect the quality of supply. This is essential to the following stakeholders in the following ways:

<u>Manufacturers of mass market electrical goods and consumers</u>: Although new regulation will bring extra costs, it will protect all appliances from emissions that can cause malfunction or failure. Reliable products are essential to consumers and are important to manufacturer's reputations. However, regulation cannot be *ad hoc* and the proposed limits must be based on rigorous, realistic and repeatable measurements.

<u>Providers of strategic infrastructure</u>: In the same way that domestic products can malfunction, so can the electronic equipment and control systems that make up key infrastructure. This might include hospital technology, mass transit systems and utilities. Whilst these systems are well-designed when compared to domestic products, unprecedented levels of supraharmonics could pose a threat to this infrastructure.

<u>Utilities, Transmission and Distribution Grid Operators</u>: An example of the threat to key infrastructure is the power grid, which is the reluctant receipt of supraharmonic emissions. Their effects include, overheating of power transformers, catastrophic failure of the capacitor banks used to regulate the power, false operation of protection circuit breakers and interference with control signals.

<u>Manufacturers of power line communication (PLC) and mains signalling equipment</u>: PLC and mains signalling use the grid wires for data transmission and for control signals, for example those used to operate smart grids. PLC intentionally emits 2-150 kHz signals into the grid, so users and manufacturers have a very strong interest in ensuring that the pollution from electronic devices does not unintentionally jam communications.

<u>Electric vehicles, renewables and energy storage manufacturers – users of power convertors</u>: These technologies are vital to CO_2 reduction and their deployment will increase rapidly in the coming decades. Power convertors are used to exchange their energy with the grid, but these electronic systems can also generate substantial supraharmonics. Power convertors are also susceptible to emissions which can interfere with the electronics whose purpose is to synchronise to the grid frequency.

Impact on the metrology and scientific communities

Development of a suitable new supraharmonic measurement system is scientifically challenging involving advanced DSP techniques, fluctuating signal analysis, data visualisation and complex impedance interactions. This will generate important publications where these techniques will be clearly described, in order to contribute to spread both the results of the work, and the contributions to the standards and new instrumentation. The project will give rise to new services for NMIs and calibration laboratories who will need to develop their measurement capabilities in the 2-150 kHz range. The Test and Measurement industry will need to respond with new instruments, AMNs which will be used in EMC Testing Laboratories for routine compliance assessments on mass market goods.

Impact on relevant standards

The main objective of this project is to produce a new supraharmonic measurement method to be included in the main PQ measurement standard IEC 61000-4-30. The convener of the special IEC 77A WG9 Task Force for this method, is this project's Chief Stakeholder who has been involved in the drafting of this project. This relationship will ensure a direct link to implement the projects outputs. The method will also be considered by IEC TC85 WG20 responsible for measurement equipment for grids.

The project will research the suitability of the normative AMNs as used to simulate the mains in EMC laboratories. This will be reported to the IEC SC77A WG1 and CISPR/H committees and recommendations as to the suitability of the existing AMN specifications will be made to the standards committees responsible for IEC 61000-4-7 and CISPR 16-1-2. Furthermore, Information on the cumulative emissions of mass-market goods in grids will be essential information for SC77A WG8 who can use the results to consider the suitability of compatibility limits as dealt with in IEC 61000-2-2.

Longer-term economic, social and environmental impacts

Electronic goods and power grid systems are essential elements of the economy and social structure. Credible and fair regulation is required to ensure that these complex systems do not interfere with each other and cause malfunction. The challenge is to set the limits used in regulation to protect the infrastructure, but not overburden manufacturers and consumers with unnecessary costs. Yet no suitable measurement method for the supraharmonics exists, so any limits are essentially an educated guess. The project will provide the long-term infrastructure to set and assess limits for mass market goods ensuring the reliable operation of products in a market worth hundreds of billions of Euros. Regulating this interference will ensure the reliable operation of smart grids and the prevent issues connecting and operating future renewable energy technologies.

List of publications

1. Measurement of 2-150 kHz Conducted Emissions in Power Networks, Ritzmann, D., Wright, P., Meyer, J., Khokhlov, V., De La Vega, D. and Fernandez, I., Proceedings of CPEM 2020, Link

2 "Comparison of Measurement Methods for 2-150 kHz Conducted Emissions in Power Networks", Deborah Ritzmann, Stefano Lodetti, David De La Vega, Victor Khokhlov, Alexander Gallarreta, Paul Wright, Jan Meyer, Igor Fernández and Dimitrij Klingbeil, IEEE Transactions on Instrumentation and Measurement, Early Access, Nov. 2020, https://doi.org/10.1109/TIM.2020.3039302

3 "A Digital Heterodyne 2 kHz to 150 kHz Measurement Method based on Multi Resolution Analysis", Paul Wright and Deborah Ritzmann, IEEE Transactions on Instrumentation and Measurement, Early Access, Nov. 2020, https://doi.org/10.1109/TIM.2020.3038290

4 "Traceable measurements of harmonic (2 to 150) kHz emissions in smart grids: uncertainty calculation", Daniela Istrate, Deepak Amaripadath, Etienne Toutain, Robin Roche, and Fei Gao, Journal of Sensors and Sensor Systems, Vol.9, Issue 2, November 2020, https://doi.org/10.5194/jsss-9-375-2020

5 "The Role of Supply Conditions on the Measurement of High-Frequency Emissions", Adam J. Collin, Antonio Delle Femine, Carmine Landi, Roberto Langella, Mario Luiso and, Alfredo Testa, IEEE Transactions on Instrumentation and Measurement, Volume: 69, Issue: 9, Sept. 2020, https://doi.org/10.1109/TIM.2020.2992824

6. A Digital Heterodyne 2-150 kHz Measurement Method, P.S. Wright and D. Ritzmann, Proceedings of CPEM 2020. Link

7. “Comparison of Measurement Methods for the Frequency Range 2–150 kHz (Supraharmonics) Based on the Present Standards Framework”, Victor Khokhlov, Jan Meyer, Anne Grevener, Tatiano Busatto, Sarah Rönnberg, IEEE Access Vol.8, Page(s): 77618 - 77630 , April 2020, https://doi.org/10.1109/ACCESS.2020.2987996

8. “Waveform Data F08_EV_PLC_Data_V2.csv” Khokhlov, V. https://doi.org/10.5281/zenodo.4271889

9. “5 sec of colored noise, tonal-narrowband and wideband NIE and PLC transmissions recorded on the LV grid voltage”, https://doi.org/10.5281/zenodo.4467784

10. “5 sec of colored noise, tonal-narrowband and wideband NIE, harmonics of tonal NIE and PLC transmissions on the LV grid voltage”, https://doi.org/10.5281/zenodo.4467777

11. “5 seconds recording of LV voltage grid with a PV inverter (switching frequency at around 20 kHz)”, https://doi.org/10.5281/zenodo.4467774

12. “5 seconds recording of LV voltage grid of colored noise, tonal-narrowband and wideband NIE, harmonics of tonal NIE, PLC transmissions and replicas of some of these transmissions”, https://doi.org/10.5281/zenodo.4467771

13. “#12 decimated to reduce sampling rate to 1MHz”, https://doi.org/10.5281/zenodo.4467764

14. “Synthetic waveform with EMI components varying at frequencies between 14.9 and 24.9 kHz varies between 1.3 and 1.7 V”, https://doi.org/10.5281/zenodo.4434268

15. “Synthetic waveform with EMI components varying at frequencies between 14.9 and 24.9 kHz is 2.2 V”, https://doi.org/10.5281/zenodo.4434267

16. “The RMS magnitude of EMI component at frequency of 19.9 kHz is 5.1 V”, https://doi.org/10.5281/zenodo.4431668

17. “EV charger with switching frequency of around 27 kHz and its 2nd harmonic”, https://doi.org/10.5281/zenodo.4431657

18. “RMS magnitude of the EMI component at frequency of 19.9 kHz is 6.9 V”, https://doi.org/10.5281/zenodo.4431658

19. “Spectrum of CPU of the desktop is loaded with 40 % of the maximum capacity (to 9kHz)”, https://doi.org/10.5281/zenodo.4419029

20. “Spectrum of induction cooker is running on the mode of 1000 W. (to 9kHz)”, https://doi.org/10.5281/zenodo.4419014

21. ”Spectrum to 9kHz of a LED lamp”, https://doi.org/10.5281/zenodo.4418969

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 May 2019, 36 months	
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Chief Stakeholder Organisation: IEC77A WG9 Task Force for the redefinition of Annex C of IEC61000-4-30 (Power Quality Measurements)	Chief Stakeholder Contact: Michael Schwenke (IEC SC77A WG9, Head of TF Supraharmonics)	
Internal Funded Partners: 1. NPL, United Kingdom 2. LNE, France 3. VSL, Netherlands	External Funded Partners: 4. TUD, Germany	Unfunded Partners: 5. METAS, Switzerland 6. SUN, Italy 7. UPV/EHU, Spain
RMG: -		