D1.5 Roadmap to Application on A/C (prop. D1.5)

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Executive Summary

This document describes the roadmap steps on how to make use of the EPICEA platform to the benefit of the stakeholders. This includes the objectives, which explains the platform applications in an industrial environment. It also concerns the planning activities and time line plus the row order of magnitude of the needed budget. Finally, the business model will also be presented and looked at.

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Deliverable Contributors

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Summary of contributions

Contributing Partners as defined in DoA	Brief Description of Contribution to the Deliverable
FE	Proposes the EPICEA technology roadmap plan and time line. Defines its objectives and rough estimate of budget planning.
BA	Defines the aircraft market need and possible product development using the EPICEA platform.
ONERA	All the parts related to the increase of TRL, from TRL3 to possible TRL5.
AXES	Technical discussions with ONERA on how to increase TRL.
ARTTIC	Quality Review of the Document before submission.

Document History

Release	Date	Reason for change	Status	Distribution
R0.1	20/06/2018	Draft version of the document provided by FE and BA	DRAFT	All WP1 partners
R0.2	24/06/2019	Completion by ONERA of the section of TRL assessment	DRAFT	All WP3 partners
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R0.4	24/07/2019	Quality Review by ARTTIC	IN REVIEW	All WP1 partners
R1.0	29/07/2019	Final version	DELIVERED	Consortium & EC

List of Acronyms / Abbreviations Used in this Document

Acronym / Abbreviation	Definition
CEA	Composite Electrical Aircraft
CooA	Coordination Agreement
CRN	Current Return Network
DCU	Electromagnetic
EFIE	Electrical Field Integral Equation
EM	Electromagnetic
ETW	Equivalent Thin Wire
EWIS	Electrical Wiring Interconnected Systems
FTL	Field to Transmission-Line
HFB	High Frequency Band
HEP	Hybrid Electric Propulsion
HIRF	High Intensity Radiated Field
IFE	In Flight Entertainment
LFB	Low Frequency Band
LIE	Lightning Indirect Effects
LRU	Line Replaceable Unit
HIRF	High Intensity Radiated Fields
IS	Interconnected Systems
ISW	Internal Source Wire
MFB	Medium Frequency Band
MTL	Multiconductor Transmission-Line
NTC	Numerical Test-Case
p.u.l.	per-unit-length parameters
SGN	Signal Ground Network
TRL	Technology Readiness Level
VNA	Vector Network Analyzer

Contents

1 Introduction

This report describes the technology roadmap of the EPICEA project evolution, by which the industrial partners and stakeholders can benefit. It presents how the platform will help to overcome:

- Challenges due to electromagnetic threat coupling with airframes ,
- Challenges faced by harness manufacturers and aircraft systems integrators for guaranteeing systems immunity on board airframes in electromagnetic environment.

It will also highlight on possible future EPICEA modules that could need further developments.

1.1 A/C Market Need

Aircraft integrators face daily challenges from different disciplines. “Time” plays an important key role in resolving any challenge. Thus, simulation platforms can then be used to ease the investigation during pre-design and design phases, for troubleshooting systems immunity and performance.

Preventing those challenges contributes to anticipate product performances, to reduce development as well certification test activities.

A three layer approach for the market need is applied, common to technology roadmaps, to identify relations of EPICEA functions needed.

EPICEA scope was to enable the vision of collaborative EMC design environment for integration of current electrical systems in an aircraft. EPICEA can also be used to enable new technologies that are being explored and are being developed. For Hybrid Electric Propulsion (HEP) challenges in the field of EMC are identified at the European research agenda ([2], [3]). Power feeders and EMI filters for power electronics will adapt to the raised level for this technology and introduce raised levels of EMI inside the aircraft to be mitigated. Wireless technologies are actually exploited for In Flight Entertainment (IFE). For future application, wireless technologies need to become more reliable and more responsive to support transport of aircraft data. For these technologies, EPICEA has a lot of functions in place that can be used with an extension to simulate aircraft internal radiated interference. For wireless technologies, the antenna simulation functions can be applied and it will need additional functions to observe reliability of a wireless connection.

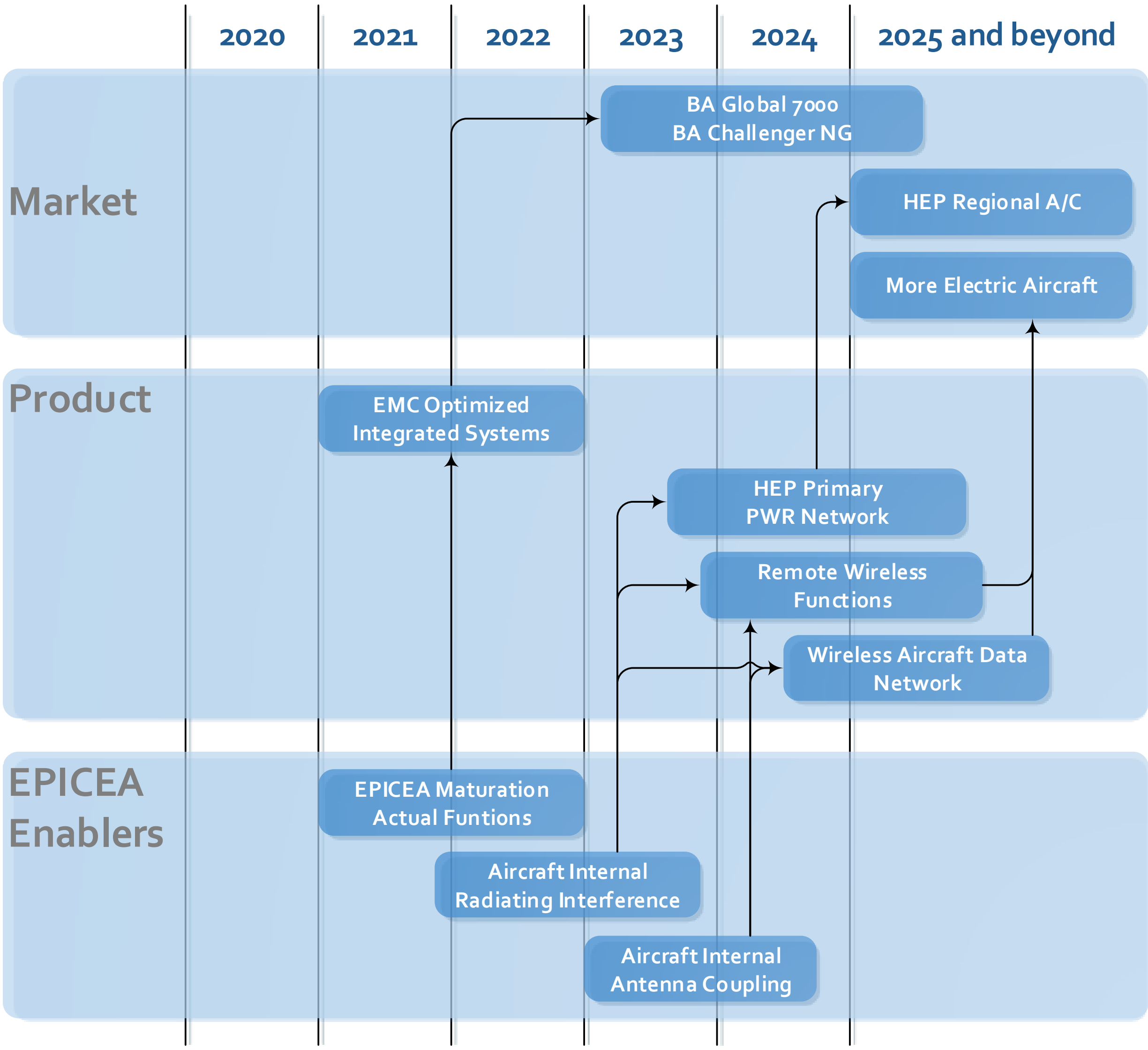

Figure 1: 3-layer approach for the market

Within the actual scope of EPICEA, and during the remainder of the document, EMC Optimized Integrated Systems are considered.

1.1.1 Target Application

The EPICEA platform can be applied to any Bombardier Aircraft, either current or new designed product. The current target use is the Global 7000 or Challenger NG.

1.1.2 Product

Within the aircraft, harness segregation can be analysed and checked against possible

- Cross talk between cables signals (inside bundles or between bundles)
- Electromagnetic energy coupling due to HIRF , indirect or direct lightning effects, as well as Static Discharge
- Emissions due to magnetic field or electric field

This analysis supports trade-off between protective measures in aircraft shielding, shielding of wiring and EMI-filter in electronic equipment to achieve the most cost and weight effective solution: EMC Optimized Integrated Systems.

1.1.3 Technology Enablers

Technology enablers are the software developers able to provide:

- The computer platform environment. In EPICEA, this environment is based on the CuToo software which offers a cooperative way to exchange data at computer module interfaces. This capability makes it possible implementation of built-in modelling scenarios in the platform involving several computer modules with specific modelling capabilities.
- The computer modules, computer software pieces with specific capabilities (i.e. pre-processing, post-processing, 3D calculation, MTLN calculation…). They are used within the various scenarios defined in the EPICEA methodology and the plugged in the platform.
- The wrappers, pieces of computer software capable to make the appropriate format translation into and to the AMELET format as well as the appropriate processing required for each EM scenario involving specific modules.
- A common language allowing communication at interfaces in the platform. It includes both the format of data and the standardization of the models In EPICEA, this language is called AMELET HDF. It is based on the HDF technology that allows appropriate handling of large data files.

2 Objective

The objective is to provide a robust EMC simulation platform that have been solidly validated to be used in level testing, validation, and can be used to predict some of the aircraft EMC compliance tests for certification. It shall also be designated to confirm harness bundle segregation requirements. Accordingly, the definition of signal frequencies and different system types should be clearly highlighted. The following Section shall highlight the aforementioned.

3 Signal Frequency and System Types

3.1 Signal Frequency

As far as propagation of signals is concerned, one must distinguish between two types of frequencies (i.e., radiofrequencies):

- Signals operating at low frequencies;
- Signals operating at high frequencies.

With regard to the low radio frequency signals, it is necessary to segregate the very low frequency signals from the medium frequency signals.

3.1.1 Very Low Frequency Signals

From a microwave point of view, a signal is said to be very low frequency if it does not exceed 500 kHz. It can be inferred that the largest electromagnetic threat that this type of signal will face is the magnetic field threat due to lightning.

3.1.2 Low and Medium Frequency Signals

Low and medium microwave signals cover frequencies ranging from a few hundred of kHz (500 kHz) to a few tens of MHz (30 MHz). These signals are sensitive to both the electric and magnetic fields.

3.1.3 High Frequency Signals

High frequency signals are signals operating between 30 MHz and 800 MHz. These signals are mainly sensitive to the combination of electric and magnetic fields and the main sources in the far field are, radio transmitters, ships, radars, etc.
The above segregation of the frequency ranges' distinction is very important in the aviation industry electromagnetic compatibility. This is because it governs the cable shield termination, as well as the necessity of overbraiding. This has a direct impact on the aircraft weight.

NB: When referring to "low" or "high" frequencies, the range of frequencies is not quite the same as in the field of telecommunications (i.e., satellites, etc.).
The above frequency range segregation is necessary, because it also contributes to make the difference between differential mode and common mode systems, which governs the use of single wire cables, twisted pair cables (or more generally multiconductor cables) and coaxial cables. This in turn has an impact on the type of cable shield termination and the cable shielding effectiveness, which affects the aircraft weight.

3.2 System Types

There are three types of systems that are listed when it is a matter of avionics and navigation systems.

3.2.1 Common Mode Systems

Common mode systems are characterized by forward and backward signals at high and very high frequencies. The electronics of such systems are bonded to the core of one side of the transmitting cable, while grounded on the other side to the casing, where the cable shield is bonded through the connector. It thus appears that the cable shield and the systems' electronics have the same ground. It is thus clear that since the forward signal propagates through the cable core, the backward signal will then propagate through the inner structure side of the box casing then through the cable shield inner side. In order to avoid the coupling between the propagating electromagnetic energy on the cable shield external side and the equipment backward signal, the cable shield must have a very good shielding effectiveness. With *t* being the cable shield thickness and δ the skin effect, then for $t/\delta \gg 1$ with Zw as the wave impedance, the shielding effectiveness SE(dB) in [1] is presented as,

$$SE(dB) = 20\, log_{10}\, ((e^{t/\delta})\frac{Z_W}{369\sqrt{F_{Mhz}\,{}^{\mu_r}/_{\sigma_r}}}) \qquad \text{with} \quad \delta = \frac{1}{\sqrt{\pi\mu\sigma F}}$$

Note: for far field $Z_w = 377\,\Omega$

Once the aircraft designer provide the immunity requirement for the interconnected systems, one can then play with the cable shield structure thickness "t" to determine the minimum thickness that still complies with SE and the skin effect equations provided above. Consequently, this will help for determining the weight of such shielding structure that is proportional to the cable shield thickness.

3.2.2 Differential Mode Systems

For Differential mode, the electronics' systems are floating inside the equipment box , and are bonded on one side to the cable conductor(s), which is dedicated to the forward signal, while the other conductor of the same cable is dedicated to the backward (return) signal. Therefore, the shield of such cable is only there for electromagnetic protection and is not dedicated to act as a signal path. That is why such on board aircraft systems can be dedicated for very low frequency spectrum; not exceeding 100 kHz.
Since the only ferromagnetic material used for cable shield is aluminium, because of its light weight, then the following condition $\delta = \frac{1}{\sqrt{\pi\mu\sigma F}} \gg 1$ is almost fulfilled because of the low frequency. With the magnetic field being the main threat, mainly in the near field, the shield structure thickness "t" can be determined as, $t/\delta \ll 1$ and the $SE(dB): -44.7 + 20\log_{10}\,(r_m\ \sigma_r\ F_{Hz}\ t_{mils})$ with $r_m \leq \lambda/2\pi$

being the distance between the emitting source and the metallic shield. F is the frequency in Hz and σr is the relative conductivity of the metallic shield respectively.
Assuming one knows the immunity of the interconnected systems, then the SE (dB) of the cable can be assessed. Consequently, one can determine the cable weight using the cable shield thickness equation defined below [1],

$$t_{mils} = \frac{\left[log_{10}\left\{\frac{SE(dB)+44.7}{20}\right\}\right]^{-1}}{r_m \ \sigma_r \ F_{Hz}}$$

3.2.3 Non Specific Systems

Those cables are dedicated to systems like switches, where no weight savings could be expected from these systems' family.

4 Technology Plan (ONERA)

4.1 Reminder of TRL at the start of the project

At the start of the project, the TRL of the project was assessed to be TRL3. It was clearly stated that no computer modules would be developed and that the cooperative modelling environment would be based on the CuToo tool that had already proved its capability for managing cooperative modelling in several cooperative projects. This confirms that the platform was mainly at a proof of concept.

4.2 TRL4 achievements

4.2.1 Technical objectives to be achieved

The objective in EPICEA was to bring the approach at TRL4, which meant according to NASA definition of TRLs "Component and/or breadboard validation in laboratory environment", with a transition between TRL3 and TRL4 relying on "technology development" in laboratory conditions for developments and validation tests.

4.2.2 Transition to TR4: "technology demonstration"

The transition to TRL4 requires a technology demonstration in laboratory conditions. In the frame of EPICEA, we understand that this demonstration mainly concerns EPICEA's methodology, based on cooperative modelling, assisted by a computer platform for the implementation of the methodology. The development of the EPICEA cooperative modelling methodology thereby required the following technological developments:

- Improvements of computer module features and their conditioning for plugging them properly in the platform
- Evolution of the Cutoo platform for EPICEA customization
- Development of wrappers for data exchange in EM scenarios

4.2.3 "Component and/or breadboard validation in laboratory environment"

The demonstration of TRL4 is based on the following topics:

- Building of various test objects:
- NTCs for cross-simulations to validate them in a full numerical environment
- The EPICEA barrel, a scale one business jet model, for comparisons between measurements and numerical simulations
- The prototype antennas for comparisons between measurements and numerical simulations

- EM Lab. Tests : two types have been considered
  - At MPB lab., on the EPICEA barrel, with local injection, LIE and ISW measurements,
  - At ONERA, POLY and FE labs., for prototype antennas radiated tests when antennas were taken separately and mounted onto metal and carbon composite plates.
- Comparisons between:
  - Simulation results having been carried out with the EPICEA methodology based on cooperative modelling scenarios, many of them inside the EPICEA computer platform
  - Measurement results having been made available by BA, ONERA, POLY and FE

4.3 TRL4 Validation status

4.3.1 Validation challenges

Carrying out the validation of the EPICEA methodology and related platform was paved with several difficulties.

Full numerical simulation validations

The "full numerical simulation", even limited on ETW configurations, proved that the methodology was robust. The main difficulty was in the coordination of the transfer of data in a coherent way especially for the definition of the central paths, the collection of the tangential electric fields and the application of the fields on the MTLN calculation model.

Validations with respect to measurements

The validation with respect to measurements presented some real challenges:

- The experimental tests were carried out at distance which means that modelers, mainly located in Europe could not attend the tests, which is normally of particular interest for them in order to really understand the test conditions. Thereby most of the modelers could not see the mock-up as well. The only visit of the mock-up could be made by ONERA who reported to IDS and AxesSim their analysis of the geometry of the mock-up. Hopefully, the availability of first version of the CAD model was very useful to explain the modifications having been carried out. Finally, even BA could not follow the tests day after day because the tests were carried out in Ottawa and not in Montreal.
- The numerical simulations of the tests were performed in a remote time because of both time and distance constraints:
  - Unexpected delay for computer developments that took more time than expected especially to validate the coherence of transfer of data of various computer-model horizons (ONERA, IDS and AxesSim). It must be also reminded that the number of computer modules was quite large.
  - Unexpected delays in mock up modifications (CTA in Montreal was no finally able to carry out the modifications that finally were made by MPB in Ottawa).
- The complexity of the mockup that can be summarized as follows:
  - The mock-up is a real business-jet barrel and its size and its weight did not allow easy manipulations (positioning, transportation). Particularly, its size imposed very large EM test facilities not available in Canada and not affordable anyway in the scope of the project.
  - The SGN and CRN definitions do not refer to usual grounding practices in aeronautics. Especially, the SGN as defined in the mock-up can be considered as an electrically floating grounding network with respect to the CRN dedicated to lightning currents. Compared to the SGN, the CRN is characterized by the fact that

there are well identified good electrical contacts with the structure (skin of the barrel). Both networks are supposed to be connected in one single point that provides the same DC electrical potential, which is actually an idealistic point of view since this situation can be broken very easily. For instance, the connections of the cable shields of the antenna coaxial cables at the level of the antenna supports directly provide unwanted other connection points of the SGN to the structure and therefore with the CRN.

- The materials constituting the barrel were unknown. Especially the barrel is made of different panels with various parts of various depths. The constitution in terms of carbon fibers, layers, lightning protection grids was unknown which made impossible the simulation of their equivalent parameters by POLY material-modelling tools (code A). The material of the composite skin was therefore considered as homogeneous, based on Zs measurements made by ONERA in various zones of the barrel.
- Some parameters of particular importance for EM simulation, especially at low frequency regimes (for lightning applications for instance) were not controlled. We mainly think of the quality of electrical contacts. The only thing that could be done in the modelling was to consider perfect contacts between the constitutive parts of the barrel. Some other parameters such as cable parameters and 3D route geometry were also not fully controlled (i.e., known with an incertitude) but are of a second order for the EM simulations.
- Some installation conditions are still under questions. We particularly think of the grounding of the B-AC-115V equipment box for which ONERA has proved by their simulation some problem with the connection of the equipment chassis to the SGN by the metallic braid. This doubt raised in April 2018 is confirmed by the Coaxial Return and ISW tests carried out by MPB (very low common mode currents measured). Note that such a default has of course an impact on the WH1 harness which is connected to the B-AC-115V, but it may also have an impact on the other connections since, the grounding of the equipment boxes significantly participated to the return of the currents (some tens of Amperes have been observed on the metal braids of the equipment boxes by simulation – see Grant Agreement D4.2 – D5.2 for the CooA). Some questions also exist concerning the quality of the contacts of connectors with the equipment cases and that may explain non-linear signatures observed in measurements. This issue was raised by FE who confirmed that specific anti electrostatic discharge device was mounted on the connectors.
- Some measurement results are under questions. This is a major issue of having the tests made at distance and with remote time analysis; problems are discovered when the tests are finished and no further verification can be made experimentally. The main questions are:
    - Nonlinear-signatures observed on LIE tests for various levels of injected currents (10 kA and 20 kA). A factor of 2 is not observed on some antenna currents and voltages. Electrical breakdown is suspected. The fact that the slow waveforms are still observed could be explained by the fact that the nonlinear effects have not occurred on the observed cables but elsewhere on the barrel.
    - Electrical breakdown signatures at some antenna current and voltages. This signature is very typical, with very fast and sharp waveforms compared to the usual “slow” waveform-A types of lightning responses. Such signatures may explain the nonlinear behaviors observed on other antennas (see above)

- S-parameters in the ISW configuration have been measured with measurement coaxial cables which is certainly an issue for low frequency measurements. Indeed, the measurement coaxial cables, and especially the shields of those cables, provide additional paths to deviate the currents. This phenomenon is not accounted for in the EM simulations that consider ideal S-parameter measurement. Those unwanted paths act as additional common mode paths that add up the SGN/CRN network. S-parameter measurements with optic fibers would certainly have avoided such an issue. This issue at low frequency is confirmed in all ISW simulation results (or more precisely in all electrical conduction response regimes of the simulation results)

4.3.2 Assessment of the validation achieved

Full numerical simulation validations

Full numerical EM validation has been successively achieved:

- A **large methodological knowledge** was gained on NTC1 and NTC2, especially on the way to implement the FTL scenarios (how to define paths, how to process E fields, how to apply them in MTLN models
- The **comparison to numerical results** achieved on ETW configurations on NTCs and the EPICEA barrel entirely validated the field calculation process made by the 3D solvers (ALICE and GALILEO) on the harness central paths as well as their applications in the MTLN model.

Validations with respect to measurements

Compared to full numerical validations based on simplified one wire harness models (ETW), experimental validations were intended to validate the FTL process as far as MTLN were concerned. At the end of the EPICEA project, we can consider that the experimental validation is « acceptable » on MTLN and antenna configurations if we consider the challenges previously mentioned. Indeed:

- **The EPICEA mock-up could not be used for antenna performance validation** but lab tests have been made at ONERA, Poly and FE with metal and CFRP planes. All simulation results gave very good agreement
- **The EPICEA mock-up has been extensively used for FLT assessments**:
    - ***LIE results*** give good levels of magnitudes even if the simulated results may be considered as too slow,
    - ***ISW results*** are not good enough at low frequency certainly because if the S-parameter measurements have been made with cables but there are very acceptable at high frequency in the resonant regions of the cable responses.

4.4 How to improve TRL4?

Even if the TRL4 has been reached in EPICEA there are still several paths to improve the robustness of this level.

Improvements on the cooperative platform

At the end of EPICEA, some actions will have still to be performed outside the EPICEA platform environment. This is not an issue for a research project and TRL4, but this may become an issue as soon as a step to TRL5 is concerned. As far as TRL4 is concerned, researchers and computer code developers may be still highly involved in the validations and can intervene inside their computer modules in order to have a relevant modelling process. To this extent, the platform brings a very important capability: the capability to import and export data, into the platform and outside the platform. However this intervention in computer modules is not acceptable as far as end-users need to apply themselves the modelling process. They need a secure modeling environment, not only for the computer modules they use but also for the computer platform that brings them a service to avoid modelling mistakes when building and running models. Such identified improvements have been listed and are reported below:

- **The CRN/SGN models**. Two modelling ways can be considered: the model as a common-mode impedance junction and the model as MTLN.
    - ***The common-mode impedance junction model*** requests having the calculation made by a 3D solver having the capability to calculate at very low frequency and making efficiently all the injections at the various connection points of the harness to the structure. This solution was the one envisioned at the beginning of the project. MoM solvers as the one developed by IDS are of particular interest from this perspective. It was not finally implemented because the investigation of the MTLN solution was preferred because it copped perfectly with the logic of wiring modelling and offered the opportunity of investigation a new modelling method.
    - ***The MTLN model*** is a real innovation brought in the project in terms of modelling of current returns. It is made possible as far as CRN/SGNs are made of long conductors (bars, braids, cables…) connected together, the reference of the MTL models being the 3D structure (in our case, the cylinder of the barrel). Compared to the common-mode impedance model, this solution is for sure an approximation but, in EPICEA, it was proved to be a reliable solution for which the modelling, even if reasonably achievable, is not easy to make. On the counterpart, the connection to the IS model is easy to make because of the compatibility of the two MTLN models and the calculation remains fast due the MTLN solvers. In the future, the improvement would be the capability to develop such a model inside the platform environment.
- **The 3D asymptotic / PWB / MTLN HFB scenario**. Such a scenario can be seen as an extension of the FTL process but applied this time at high frequency. As a first step, the combination of the asymptotic code and the PWB code allows calculation of the field environment at the level of the cables as in the FTL process with the 3D full wave solvers. As a second step, the field environment calculated by PWB is synthetized as a Plane Wave spectrum on a scenario relevant from the usual process (based on CRIPTE's RANDOMOP module). The whole process has been defined and validated in the EPICEA project but it still requires significant work to be implemented in the EPICEA platform with the required computer automation level.
- **The material equivalent matrices including surface impedance and transfer impedance** The surface impedance capability now exists in all 3D full-wave solvers but the transfer impedance capability is barely implemented. The reason is that the model requests a significant increase in memory and computation time of the model. The problem is even more complex for time domain solvers since this modelling capability requires dispersive capability modelling (parameters depending on frequency). However, this capability is absolutely required for carbon composite enclosures such as full tanks. In the EPICEA barrel, this feature was not required because the barrel was opened with 8 windows. As far as the frequency increased, as expected by EM physics, the scattering through the windows overcame the EM diffusion in the carbon composite materials.

<u>Improvement on the reference measurements</u>

The experimental validation suffers some « holes » in the demonstration. Such holes exist because of resource constraints (time, budget, people, objectives) dictated by the frame of such projects. However, we have identified several actions that would have been worth being done in order to help convincing on the validation argumentation.

- **Build physically NTCs**. The NTCs are well controlled objects (in terms of geometry and electrical parameters). Such NTC have been built numerically and helped validation at numerical level. However, such limitations are limited to ETW-models which makes impossible validation at MTLN level. If experiments had been done on NTC1 and NTC2, they would have withdrawn the possible doubt on the pertinence of the simulated results. However, such validations on canonical objects with comparisons with measurements have been done for a long time and are available in the references of the EMC community for metallic objects. Nevertheless, they are bare as far composite carbon structures are concerned.
- **Perform verification tests on the mockup** since several questions have been raised on the installation conditions of the wiring and on the pertinence of the measured results. The ideal world would have considered tuning and simulation at the same time. Indeed, even if in a validation process, the computer modules together with the computer process would have been mature enough to give physical trends allowing one to detect measurement problems. Those verification tests would include:
    - ***Verification of the mock-up installation****:*
        - Check of grounding braids of equipment
        - Check of electrical contacts of connectors
    - ***Verification of measurements techniques*** with a sensitivity analysis.
        - Confirm linearity of results for LIE, after checking the installation, by injecting several amplitudes of waveform A
        - Measure the LIE currents on the equipment braids and check the influence of disconnecting some braids on the barrel
        - Analyze the S-parameter measurement techniques for ISW configuration and check the possible difference between measurements by cables and fiber optics.
        - Make plane wave validation (HIRF) in a facility allowing such tests or in open air test facilities. Such facilities would allow testing antenna radiation but in a specific condition (with the presence of a ground difficult to fully control from an electrical characteristics point of view). From this perspective, the tests in MSRC were very relevant in the frame of the EPICEA project.

<u>Extension of EPICEA barrel applications</u>

So far, the electrical system installed on the barrel is a passive system. Especially, the equipment boxes are dummy boxes. However, the electrical functions and the wiring are close to a real definition. So we could imagine replacement of the currently available passive wiring circuit with active circuits in order to demonstrate the capability of the EPICEA approach to carry-out EM susceptibility and EM emission assessments. The simulation could remain passive as defined in EPICEA's methodology but the calculated current and voltage constraints would have to be compared to the susceptibility level of each active function. This would require a characterization of the equipment boxes in terms of impedances as well as determination of the susceptibility level of the functions.

4.5 Roadmap to go over TRL4

So the question is what remains to be done to go over TRL4. At this stage of the project, the evaluation mainly concerns the achievement of TRL5. In the next chapter, extrapolation to higher TRLs and full exploitation by end-users will not be limited to technical aspects: it will also concern budget and business plans. So from a technical point of view, as done for TRL4, we can characterize the TRL achievement by the two criterions concerning:

- The transition from TRL4 to TRL5
- The assessment of the TRL5 level

4.5.1 Transition to TRL5: "technology demonstration"

Whereas the transition to TRL4 was based on a technology demonstration in laboratory conditions which perfectly matches the objectives of the EPICEA project, the transition to TRL5 requires a technology demonstration this time in relevant environment. Whereas EPICEA's transition to TRL4 only concerned the methodology, we understand that this TRL5 transition requires the full validation of the EPICEA platform deployed within an end-user (airframer or airfraimer supplier) environment including all its development program constraints, from design to qualification/certification phases. Of course such a transition will start from the reinforcement of EPICEA's TRL4 described above and will be based on significant technological evolutions:

- **Improvement of the EPICEA platform with all the EM scenarios entirely plugged** inside the EPICEA platform (see TRL4). This evolution must not concern only the modules proposed within the EPICEA project but other new modules. We think for instance of 3D FDTD modules coming from EMA Technology used by Bombardier Aeronautics.
- **Extend the modelling capabilities of the platform**. The EPICEA platform mainly aims at EM. However, this platform can be part of global development process for which other constraints related to electrical installation must be concerned. This is particularly the case for the evolution of future aircraft towards full electrical concepts for which electrical constraints cannot be separated form heating constraints. This means that heating of cables and heating of the 3D structure at cable (or braids) connection points to the structure should be addressed including electricity, EM and heating as parts of a global optimization process. The alternative will be to integrate this heating process into the EPICEA modelling environment or to establish bridges with other existing heating calculation environments. The question still remains open today.
- **Prepare cable architecture environment** for EM simulation. We have seen that a key enabling capability of EPICEA's methodology relies on the capability to capture the EM model of complex cable architectures. In the project, the model of the EPICEA-IS could be made by hand because the size of the problem was small. However, such a hand-made operation is not achievable for real aircraft programs for which the building of the MTLN must be done automatically from the wiring and installation data available in the end-user data bases. Such a capability requires an investment from end-users: the creation of the aircraft cable architecture which requires a merging of the 3D structure and the cable installation information. This also requires close cooperation and clear data communication between suppliers and airframers because both types of information generally come from each of those end-users.

4.5.2 TRL5 objective: Validation in a relevant environment"

The transition to TRL5 being made we must now imagine what kind of validation must be addressed at TRL5 for application in a relevant end-user environment. We have identified so far 3 main actions. Others main be identified in the future but those ones seem to be mandatory from a relevant environment exploitation point of view:

- **Apply the process and platform in an industrial program**. This requires the availability of the cable architecture of the wiring of a real aircraft program as well as the EPICEA platform available with all required EM scenarios plugged-in.

- **Optimize as a whole on weight/geometry/EM protection and heating**. This global optimization process is one of the main objectives in terms of design. It does not concern only the weight of the EWIS constituents (cables, connectors, cable shields…). Since weight increases with length of cables, the capability to analyze various routes for point to point connections while maintaining segregation may significantly help reducing weight impact
- **Compare to real standards**. Compliance with the aircraft specification is another mandatory objective of the end-users. For this, what is calculated by the platform must be compared to what is required by standards. In the frame of EPICEA, the scope of compliance is mainly aiming at aircraft level which means it mainly concerns ARPs. However, it is fully possible to think of using the EPICEA platform to simulate laboratory tests on equipment as described in DO-160.

4.5.3 General comments

The step towards TRL5 is a mandatory objective of the EPICEA roadmap. However, all stakeholders (academia, laboratories and end-users) must keep in mind that EPICEA's methodology being based on modelling, the models and sometimes the methods are likely evolve in time. This means that two contradictory objectives must keep being carried out in parallel:

- **The application of EPICEA at TRL5**. This is absolutely mandatory in order to push the application to real environment constraints, even if the performance of the methodology may not be perfect because:
    - ***Some models may be imperfect*** but we must keep in mind that a model is just a simplification of a real problem compliant with a commonly agreed level of acceptance. For instance, for standardization, it is common to have very crude models, for which the application domain is not sometimes even relevant and that no end-user will question because everybody accepts it.
    - ***Input data may be missing***.
        - *In some cases, the information does not exist.* This is the case for the input impedance of equipment (or more generally, the circuit model of the input of the equipment). Only equipment suppliers have the capability to provide this information. This is not done so far. The reason is likely to be that this information was not judged by them worth being generated and provided since there was no real place to use them yet. Nowadays, with the project achievements, we can demonstrate that there is a place for equipment input impedance data in a global wiring simulation. A similar evolution was observed for electrical wiring suppliers. For a long time, the only EM modelling and measurement activity was modelling of transfer impedance of cable shields, whereas the MTLN theory already existed and was at validation step in laboratory. The capability demonstrated by several end-users to generate the large and complex MTLN models really changed the objective from a scientific topic to be developed to an industrial process to be implemented.
        - *In other case, the information exists* but it is not fully available for EM modelling when it is required. This is the case for example for the constituents of carbon composite materials. We could imagine that this information could be stored in data bases available for structural resistance evaluation but also for EM characterization calculation. We could also imagine that when built, samples of materials could be tested on the production chain in terms of surface and transfer impedances. At the same

time junctions between material panels could be tested as well with the common objective to feed data bases for EM simulation purpose.

- **Research on models and methods must go on**. There are still improvements to do for models and methods, which implies accepting to go down at lower TRL and inject them back at TRL5 after. The important aspect is that the general modelling methodology is not questioned. For example, the question of breaking down the model of very large wiring systems will appear as soon (but only when) the full wiring architecture of an aircraft will be considered. It seems unrealistic today to say that such an aircraft wiring will be approached under FTL methodology. It may be unrealistic from a calculation performance point of view and because of the limitation imposed by the transmission line model which makes some specific installation configurations difficult or impossible to simulate with the level of precision required. The idea would be more to concentrate on parts of the wiring (for example specific ATAs and their wiring) with MTLN model and to model the remaining wiring as ETW. The research question will then be how to make a realistic global model accounting for those two types of models, one detailed, one crude, whereas both wiring parts share common electrical connections.

5 Plan and Budget

Key to success of EPICEA is to make the technology significant from an industrial point of view. For that, targets are set for evaluation (5.1). Not all evaluations were made before the end of the project and both FE and BA aim to do this evaluation to prepare continuation of EPICEA. Both FE and BA apply a stage-gated process for technology developments are based upon different business disciplines (e.g. Technology Business Case, Business Development, Engineering Tools and Methods, Materials, Supply Chain etc.).

5.1 Target

The following quantitative targets are set by BA and FE to evaluate EPICEA's significance:

- **Returns (on investments to be made)**
    - EWIS
        - Weight reduction: 5%
        - Cost reduction: 5%
    - Harness segregation optimization
        - Less space
        - Less complexity
        - Easier installation and final assembly
    - A/C structure
        - Weight reduction 1%
    - EMC tests cost reduction 25%

Apart from these targets, also following qualifiers for new customers apply:

- For FE, EPICEA can contribute to the significance of the EWIS Optimization R&T program, which is a qualifier for all new aircraft programs
- BA will be enabled in competitive advantage in high performance business jets (selling point is not only costs and weight, but also range)

5.2 Plan

In the coming five years, the plan is to rely on the EPICEA simulation platform to provide pre-compliance validation with test results anticipation and try to explore more parametric and test cases. The following 4 steps are foreseen to prepare exploitation:

1. Development of a Technology Business Case (TBC)
2. Preparation of the follow up on EPICEA development to mature the technology
3. The maturation itself of EPICEA
4. Technology insertion with the purpose to exploit
5. Exploitation for BA's Next Generation of Aircrafts

The schedule of this plan is shown in Figure 2.

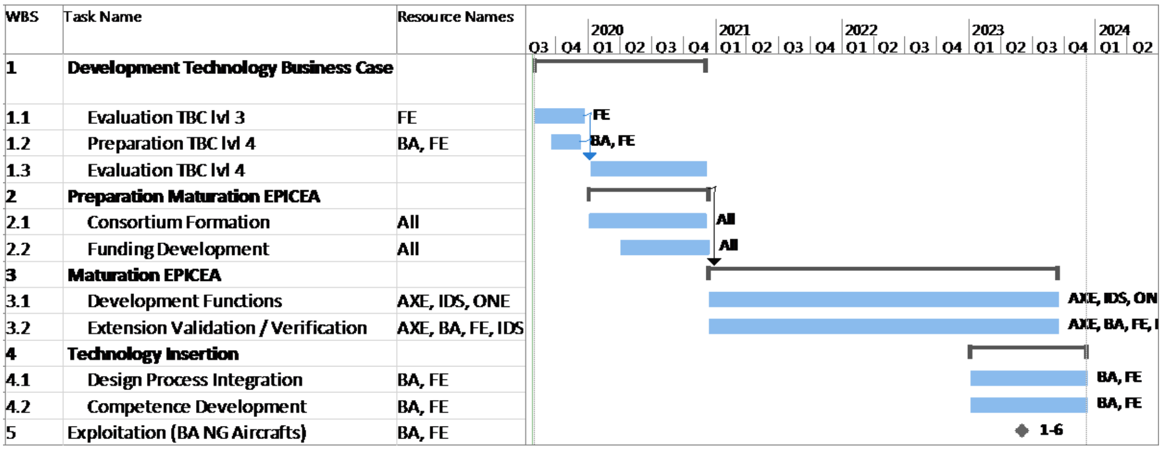

Figure 2: Schedule Road to Exploitation

- **<u>Phase 1: Development Technology Business Case</u>** Additional EPICEA simulations are performed to estimate benefits. This estimate will have limited accuracy and will be compared with investment required (target in §5.1 against budget in §5.3) to prepare a decision to proceed:
  - (1.1) During the remainder of 2019, FE will perform simulations using EPICEA to investigate parameter sensitivities in preparation of EWIS optimization. Then at limited scale according the reference inter connection system, a benefit estimate will be made at limited scale to estimate quantitative benefits.
  - (1.2) Anticipating positive outcome of (1.1) a plan will be defined to simulate a case that is representative for a next generation business jet. The plan will be proposed internally preparing a decision to proceed. It is a joint effort of BA and FE that will need support of an agreement and strategic alignment.
  - (1.3) Simulation and evaluation of actual design rules and practices, will substantiate the benefit EPICEA can put to the table at exploitation. This will affect the willingness to invest from the end-users.
- **<u>Phase 2: Preparation Maturation EPICEA:</u>** In parallel to development of the TBC, follow up on EPICEA will be prepared.
  - (2.1) For that extension more end-user will be explored. Participation of a system supplier for power distribution networks would be an extension enabling envisioned trade off at systems integration level, where EMC measures in the airframe, EWIS and electrical systems can be traded of to achieve a better prediction of electromagnetic compatibility and to achieve a more affordable solution. Also participation of competitors of BA and FE will be explored in case such participation

can be scoped to pre-competitive research and development and actual stakeholders can feel comfortable with it.
    - (2.2) both European and national funding opportunities will be aimed for with the purpose to co-fund towards industrial partners and to disseminate solutions to the market.
- **Phase 3: Maturation of EPICEA:** Maturation of the EPICEA simulation platform, will contain extension with (3.1) functions to exploit it in an industrial engineering environment. These functions will depend on how the technology will be implemented in this environment (see 4) but also to actual experiences in practising simulations in 2019 and 2020.
    - (3.1) extension with functions to exploit it in an industrial engineering environment.
    - (3.2) to mature EPICEA from a technical point of view, actual validations and verification will need extension, e.g. extension of the verification frequency range of composite structures and outcomes of a parameter sensitivity analysis performed in (1.1).
- **Phase 4: Technology Insertion:** Technology insertion is the last phase preparing exploitation. Engineering design process, design applications, design functions, product life cycle management/product data management, IT and EPICEA all have their architectures that need to be aligned and interfaces have to be build or changed to insert it in the (4.1).
    - (4.1) Design process.
    - (4.2), in parallel the Engineering competence need to be extended to prepare for
    - (5) Exploitation. Some overlap between (4) and (5) is allowed and in the early part of the (5) exploitation, EPICEA can be used for trading off different concepts or preliminary design.

5.3 Budget

A raw budget estimate is made to provide a realistic input to decision taking in the stage gated process. Working on a proposition of follow up will increase fidelity of these figures at every stage of the road to exploitation – e.g. effect of EPICEA to Engineering based non-recurring costs will be considered in a later stage. The actual raw figures available are provided in Table 1.

Table 1: actual raw figures available

WBS	Activity	Costs (k€)	Comment
1	Development Technology Business Case level 3	40 + 160	40 to TBC lvl 3 and the rest for TBC lvl 4
2	Preparation Maturation EPICEA	120	All should lead to a proposal, cost are usually in the overhead costs and distributed over all stakeholders
3	Maturation EPICEA	2000	To be revised when content is more specific
4	Technology Insertion	1000	
5	Exploitation	370	

6 Business Model

The business model considered for further development is the following. BA is responsible for systems integration and related EMC design. FE will perform EMC design and determine a transfer function during/after the detailed design. FE will also manufacture EWIS (design build program). Electrical system supplier(s) participate in exploitation of EPICEA under similar conditions as FE (design and build).

The EPICEA simulation platform will be commercially exploited by IDS and AXES. ONERA have an assistance role during exploitation, for making available future evolutions of CRIPTE and ALICE solvers.

The above assumes FE can deliver a benefit of doing EMC design during detailed design of EWIS. This scenario needs support of a liability agreement to be developed. In case FE can deliver no benefit in doing EMC detailed design, there is reason to reconsider the business model.

Not all relevant EMC related data from electrical system suppliers is an issue identified. Participation of Electrical System Supplier (UTC?) responsible for power network under similar scope and conditions as FE supplier will be explored to mitigate this effect.

7 References

[1] D. R.J. White, *Electromagnetic Shielding Materials and Performance*, Donald White Consultants, Inc. 1986.

[2] *H2020 Work Program 2018-2020*, LC-MG-1-7-2019: *Future propulsion and integration: towards a hybrid/electric aircraft*

[3] Aerospace Technology Institute, Insight 07 - *Electrical Power Systems*