# Methodology and Tooling to Promote Flight Software to ECSS Category-A

## Guidelines, tools, and examples

Andoni Arregui, Fabian Schriever

2024-06-04
Final Presentation Days, ESTEC

GTD GmbH

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# Motivation

# Do we care?

What is this?

# Do we care?

What is this?

The Boeing CST-100 Starliner

# Do we care?

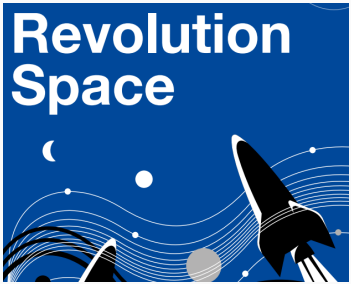
*"**We are no longer building hardware** into which we install a modicum of enabling software, **we are actually building software** systems which we wrap up in enabling hardware. Yet we have not matured to where we are uniformly applying rigorous systems engineering principles to the design of that software. These are serious and pervasive issues that NASA will need to address in all of its programs and certainly will be critical to space exploration endeavors."*

**Patricia Sanders** –
NASA's Aerospace Safety Advisory Panel Chair

# European Need for Category-A Software

**Why does Europe need Category-A Qualified Software?**

- To **continue being a player** in international cooperation and
- **achieving autonomy** in access to space.




Revolution Space report

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**ATV** 5 units flown between 2008 and 2015

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**Orion European Service Module** 6 units contracted for the Artemis missions

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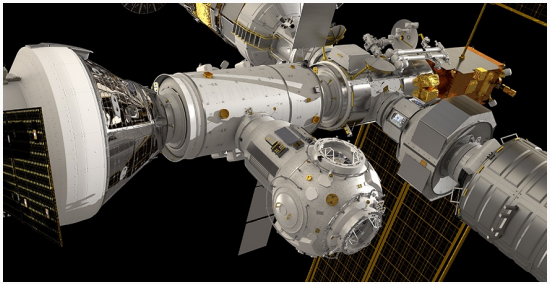

**I-Hab and ESPRIT Refueling Module** built for the lunar gateway

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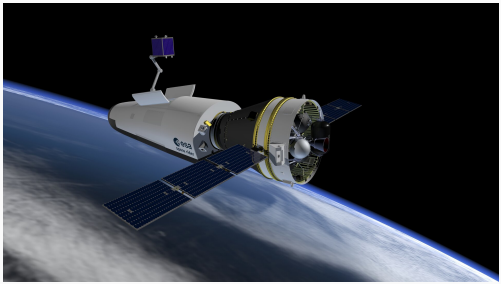

**Space-Rider** first one to be launched end of 2024

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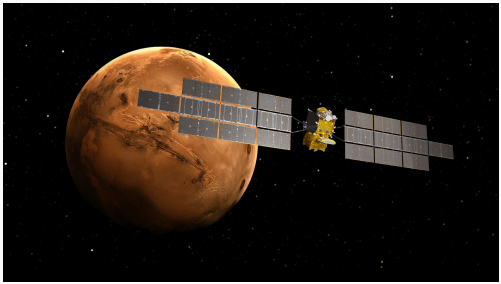

**Mars Sample Return - Earth Return Orbiter**

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**ADRIOS** launch in 2026

# ECSS Category-A Software

# ECSS Requirements for Category-A Software

**What is needed on top of the Category-B requirements**

- **MC/DC** structural coverage
- **Verification** of added **Object Code**

# E-ST-40 Requires

Full **MC/DC** coverage

## 5.8.3.5 Verification of code

b. The supplier shall verify that the following code coverage is achieved

| Code coverage versus criticality category | A | B | C | D |
|---|---|---|---|---|
| Source code statement coverage | 100% | 100% | AM | AM |
| Source code decision coverage | 100% | 100% | AM | AM |
| Source code modified condition and decision coverage | 100% | AM | AM | AM |
| NOTE: "AM" means that the value is agreed with the customer and measured as per ECSS-Q-ST-80 clause 6.3.5.2. | | | | |

*EXPECTED OUTPUT: Code coverage verification report [DJF, SVR; CDR, QR, AR].*

NOTE This requirement is met by running unit, integration and validation tests, measuring the code coverage, and achieving the code coverage by additional (requirement based) tests, inspection or analysis.

c. Code coverage shall be measured by analysis of the results of the execution of tests.

### 3.2.18 modified condition and decision coverage

measure of the part of the program within which every point of entry and exit has been invoked at least once, every decision in the program has taken "true" and "false" values at least once, and each condition in a decision has been shown to independently affect that decision's outcome

NOTE A condition is shown to independently affect a decision's outcome by varying that condition while holding fixed all other possible conditions.

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**Unique Cause MC/DC**

This understanding of MC/DC is deprecated since 2001 (CAST-6 DO-178B) and will be amended in the E-ST-40 revision

# E-ST-40 Requires

e. In case the traceability between source code and object code cannot be verified (e.g. use of compiler optimization), the supplier shall perform additional code coverage analysis on object code level as follows:

| Code coverage VS. criticality category | A | B | C | D |
|---|---|---|---|---|
| Object code coverage | 100% | N/A | N/A | N/A |
| NOTE: N/A means not applicable. | | | | |

## What is needed on top of the Category-B requirements

- **Verification** of *added* **Object Code**

# Q-HB-80-04 Requires

**Table A-5: Test coverage requirements**

| COVERAGE TYPE | CRITICALITY CATEGORY | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | |
| Statement Coverage (Source Code) | 100 % | 100 % | 100 % | AM | |
| Statement Coverage (Object Code) | 100% | AM | AM | AM. | |
| Decision Coverage (Source Code) | 100% | 100% | AM | AM. | |
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**Only statement, no decision coverage on object code?**

Branches in object code will not be properly exercised.

# European Challenge with Category-A Software

**We are not used to it**

- *SW Engineering*:
  - Neither to comply with its **requirements**
  - nor to produce the required **evidence**
- *SW Product Assurance*:
  - Neither to **interpret** the evidences
  - nor to ask the right **questions**

# European Challenge with Category-A Software

**Past Cat-A approaches sometimes flawed**

- ATV MSU: Only does condition coverage on object code, no MC/DC[1].
- ESM PDE: Requires *atomic decisions*, losing MC/DC error detection capacity and seems to incorrectly assess object code traceability[2].

[1] §5.2 in *Category A Software Development for the ATV*, Boudillet, Berthelier, Zekri, 2005

[2] §3.5 and §3.7 in *Critical Software for Human Spaceflight*, Preden, Kaschner, Rettig, Rodriggs, 2019

# Main Concerns with Category-A Software

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   ⇒ MC/DC is required for Cat-A

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5. Has the **ISVV** activity been **adequately** carried out in accordance with the required criticality level?

   ⇒ Tasks like IVE.CA.T3 do not even require unit tests to be cross-compiled for target

# Importance of MC/DC

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Restructuring source code on purpose will lower its error detection potential.

**This complex decision:**

```
bool complex_decision(bool a, bool b, bool c, bool d) {
    return ((a && b) || (c && d));
}
```

Will require 4 tests to achieve MC/DC.

*NOTE*: The 4 test cases refer to the ones needed to achieve the so called *masking* MC/DC with a number of tests $2 \cdot \lceil \sqrt{n} \rceil$, where $n$ is the number of conditions in the decision.

# Importance of MC/DC

## Rewriting it as

```
bool complex_decision(bool a, bool b, bool c, bool d) {
    bool result = false;
    if (a && b)
        result = true;
    if (c && d)
        result = true;
    return result; }
```

Will *only* require 3 tests and will fail to detect a regression if the `if (c && d)` decision is removed.

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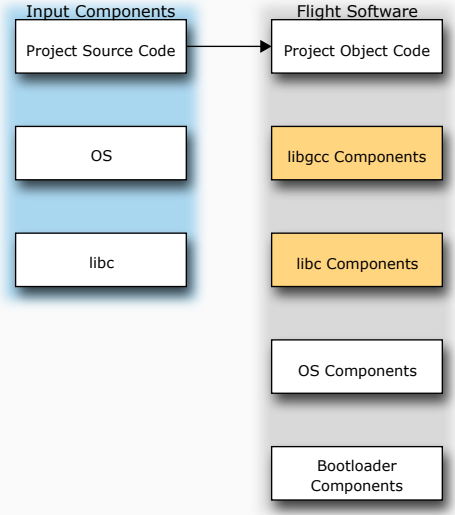
**Note:**

Coding standards enforcing **atomic decisions** are **cheating** on MC/DC.

# Importance of Added Object Code Verification

**Flight software** is usually composed of **more than only the project source code**:



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**Added object code in flight software**

1. Elements from the compiler library such as `__muldi3` from `libgcc`
2. Elements from the standard C library not explicitly called by the source code such as `memset()`
3. Array bounds checks and other side effects.

# Importance of Added Object Code Verification

**You won't notice at first these elements being added**

Adding a modulo operator on 64 bit integers will do this on SPARC V8 architectures:

```
unsigned long long int func (unsigned long long int a, unsigned long long int b) {
    return a % b; }
```

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```
func:
save    %sp, -96, %sp
...
mov     %i0, %o0
call    __umoddi3, 0
...
restore %g0, %o1, %o1
```

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**SW Engineering Question:**

Are all functions called within the object code also described in our design?

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Compilers generate **extra branches** and **rearrange execution paths** for optimization purposes.

**Structural coverage on source code not sufficient**

The project has **no evidence** that these **new branches and path** structures have ever been exercised or **verified**.

# Importance of Added Object Code Verification

**The structure of your object code is not the same as your source code**

Compilers generate **extra branches** and **rearrange execution paths** for optimization purposes.

```
int function_1 (int n) {
    int total = 0;
    for (int i = 0 ; i < n ; i++) {
        total += i & n;
    }
    return total;
}
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}
```
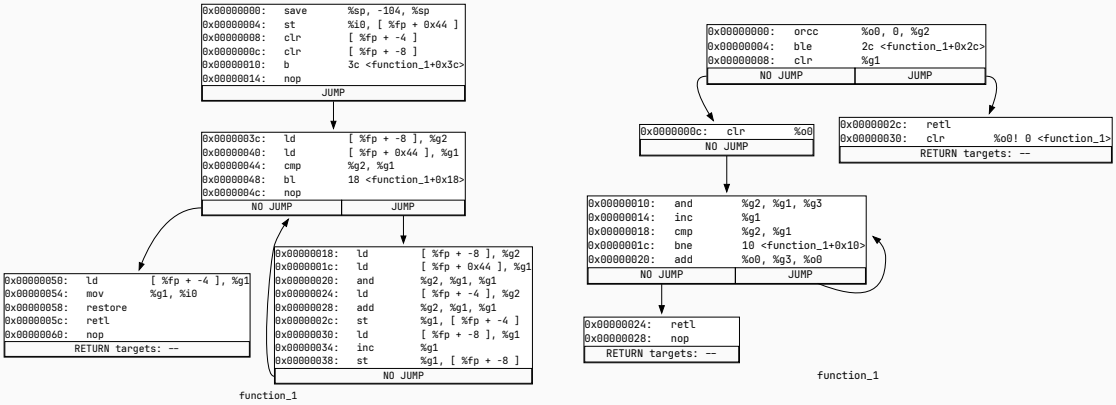

**SW Engineering Question:**

Can we prove that our object code has no untested branches?

# Importance of Added Object Code Verification

Source code structural coverage will require only one test (left side); to achieve complete object code coverage two are needed on the optimized code (right side).



# The Guidelines and Tools We Developed

# The Contract

## Contractual Context

The work has been carried out under ESA Contract No. 4000138220/22/NL/AS/adu in 2022 and 2023.

- ESA aimed at the development of a method and its corresponding tools to systematically promote ECSS Category B software to Category-A.
- All the work has been carried out with **great support** of ESA TO **Andreas Jung** and PA **Isabelle Conway**.
- Get the guidelines and tools: https://gtd-gmbh.de/cat-a/

## Methodology

- Step-wise systematic method to cover the two main gaps:
  - **MC/DC** Coverage (Referenced by NASA-HDBK-2203; to be integrated in the NASA CAP)
  - Verification of **added object-code** (Often called additional object code verification)
- Examples and FAQs

# Methodology and Tools

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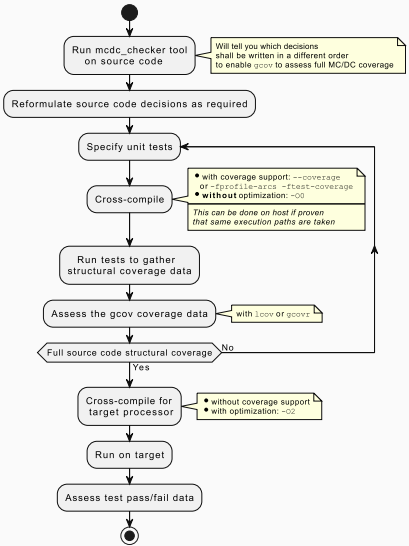
## Tools

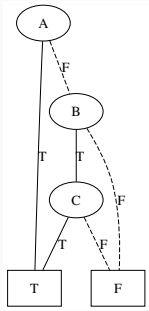
- All open-source based (Alternatively proprietary tools can be used)
- Assist in the following tasks:
  - Assess **MC/DC** coverage
  - Gather structural **coverage on object code** (On a function basis)
  - Construct function **object code Control Flow Graphs** and assist in the object code structural coverage assessment

# Assessment of Structural Coverage



# Assessment of MC/DC

The methodology proposes a tool (`mcdc-checker`) to **assess** the source code **decision structure** so that afterwards the standard tool **gcov** can be used to **assess MC/DC**.

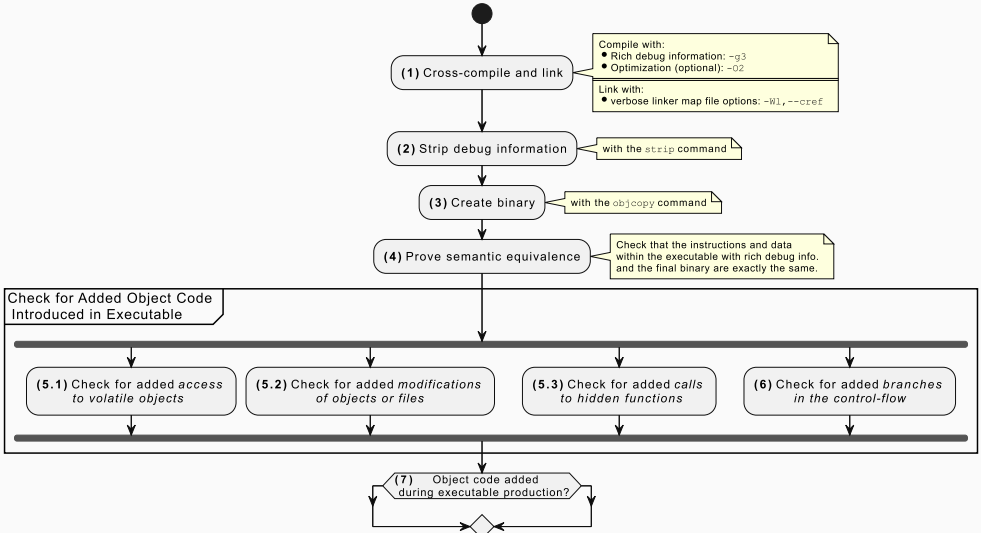



BDD for $a \vee b \wedge c$

```
4          :           : /* Correct implementation where gcov requires MC/DC */
5          :         3 : bool version_1(bool a, bool b, bool c)
6          :           : {
7          :         3 :     bool result = false;
8          :           :
9          :         3 :     if (a || (b && c))
[ +  +  +  -  :
   +  +  ]
10         :         2 :         result = true;
11         :           :     else
12         :         1 :         result = false;
13         :           :
14         :         3 :     return result;
15         :           : }
```

Structural coverage equivalent to MC/DC

# Assessment of Added Object Code



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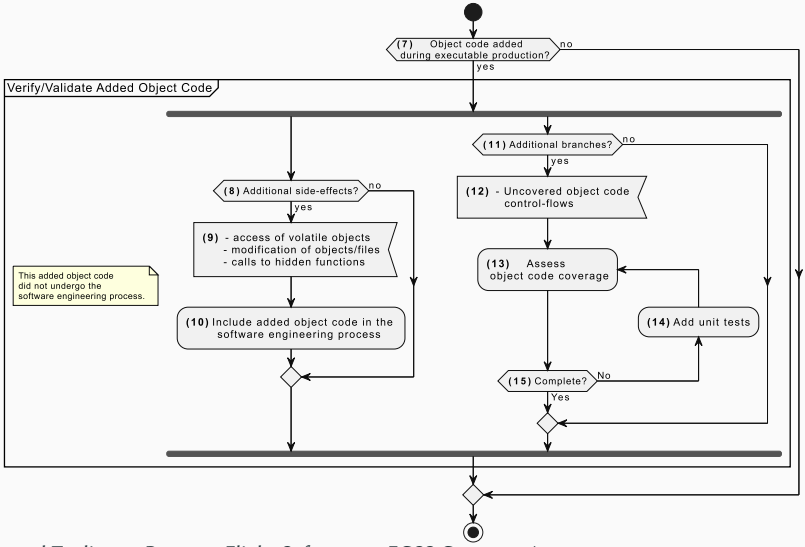
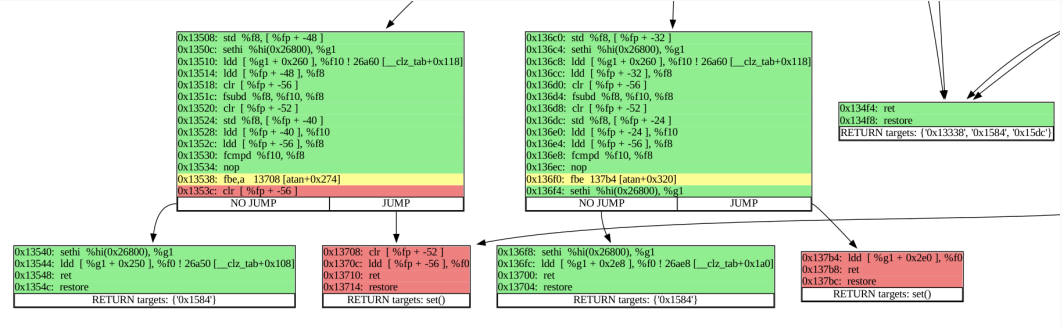


# Assessment of Object Code

The methodology helps assessing the existence of object code added during the executable production and proposes tools to gather **object code** condition **coverage** (`occtre`) and present it on the **CFG** of each function (`asm2cfg`).



# Some Self Criticism

**We shall distrust the compiler for Category-A software**

1. Object code analysis information based on DWARF debug information generated by the cross-compiler.
2. Does the cross-compiler and/or linker add extra object code we are not detecting?

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## Use complementary tools for more independence

1. Assessment tools can come from different cross-compiler.
   - Newer versions can be used.
   - `llvm` analogous tools can be used substituting GCC/binutils.
2. Linker information to cross-check compiler generated information.
3. Completeness of bidirectional object to source code traceability can be verified.

# Takeaways

# Some Best Practices

**Software Engineering/Validation shall ask itself if**

1. **Structural coverage** data has been gathered **only with unit tests** (good) or also with validation tests (bad).
2. Source code **structural coverage** has been gathered with **non optimized compilation**.
3. **Unit tests** have been **cross compiled** and executed on target.
4. The project **verified function symbols** in object code that **come** from **outside** of the project source code.

# Some Best Practices

**Software Development Processes shall not**

1. Allow **source code** to be rewriten with **only simple decisions** (e.g., `if (A)`).
2. Allow gathering **structural coverage** data only on optimized **object code** (and not on source code).
3. Accept **completeness of object to source traceability** only because **source traces** for all object code addresses have been **produced**.
4. Accept **object code coverage** is complete by checking **all project source code functions**.