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On-board software laboratory

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Objectives

- General: introduce the structure and functionality of a computer system used in space missions
- The labs: introduce the development process of embedded software of a data handling system:
  - Software implementation
  - Environment installation and setup
  - Cross development

Grade weighting

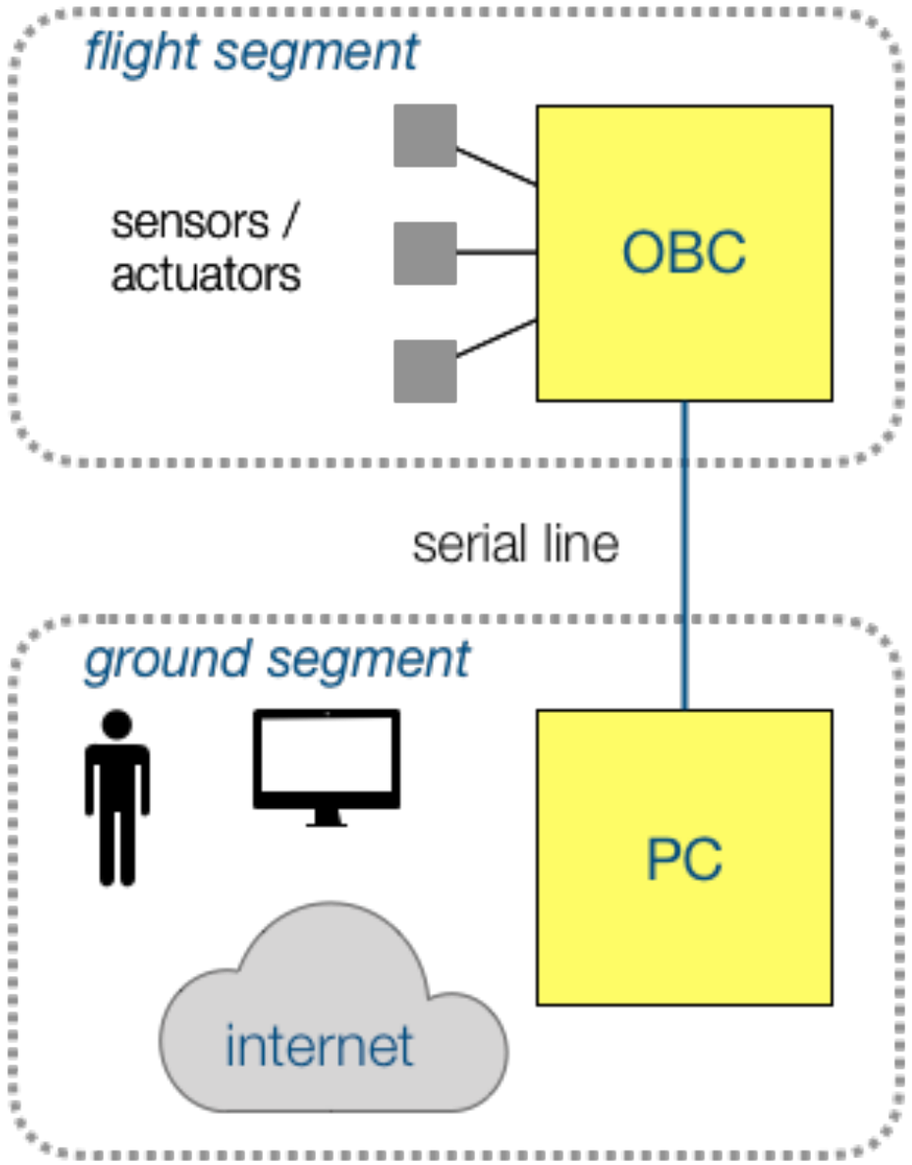
- *Prácticas 50 %*
  - *nota_prácticas = 0.3*nota_OBC + 0.7*nota_LAB*

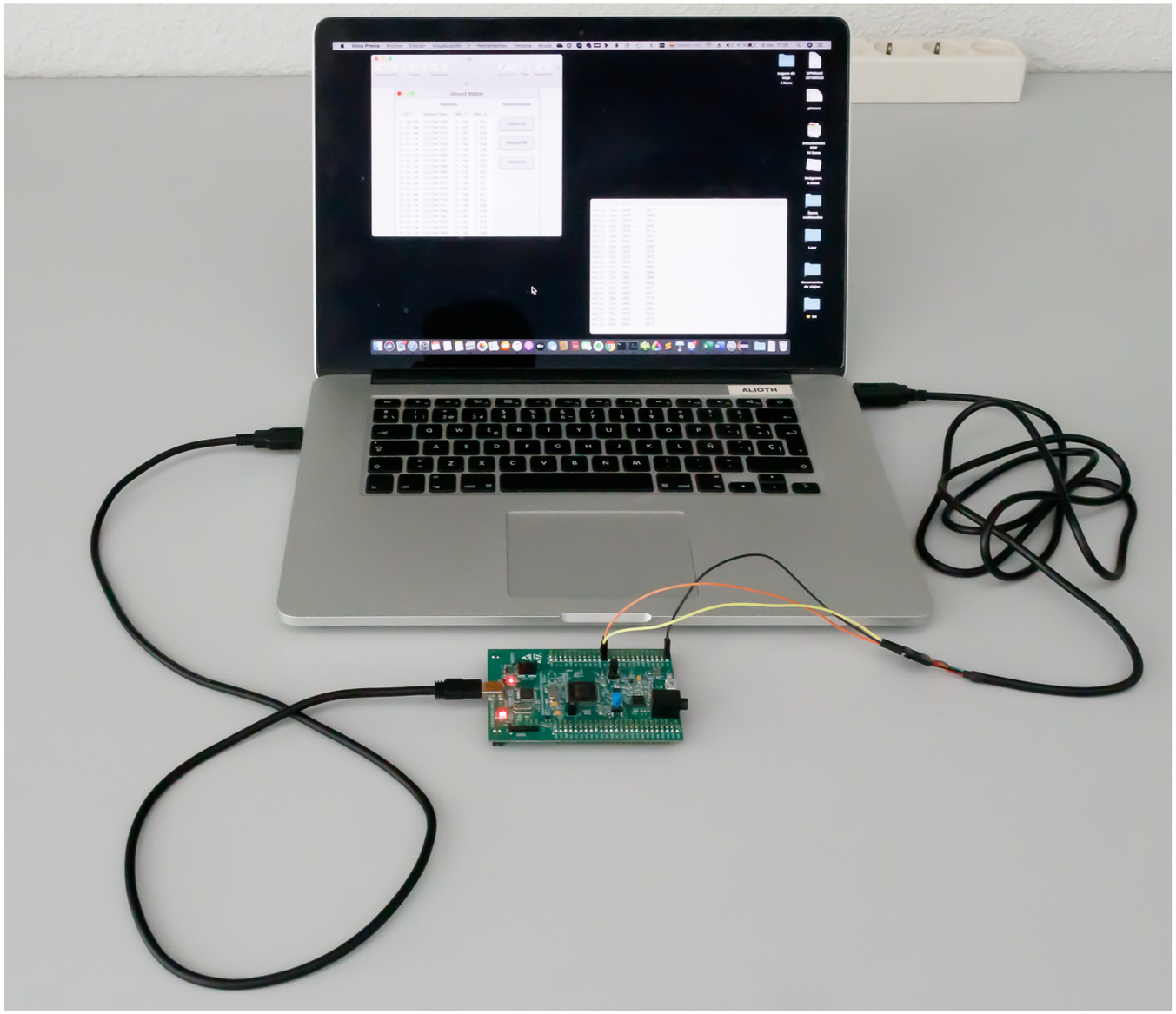
- *Nota final = 0.5*nota_examen + 0.5*nota_prácticas*
  - *mínimo de 4.0 en cada nota parcial*

Laboratory assignments

1. Installation of a native programming environment.
2. Installation of the cross-platform programming tools.
3. Simple housekeeping program.
4. Tasking program.
5. Distributed housekeeping program.
6. Real-time program, including temporal analysis.
7. Real-time program with attitude control system.
8. On-board data handling (OBDH) system.

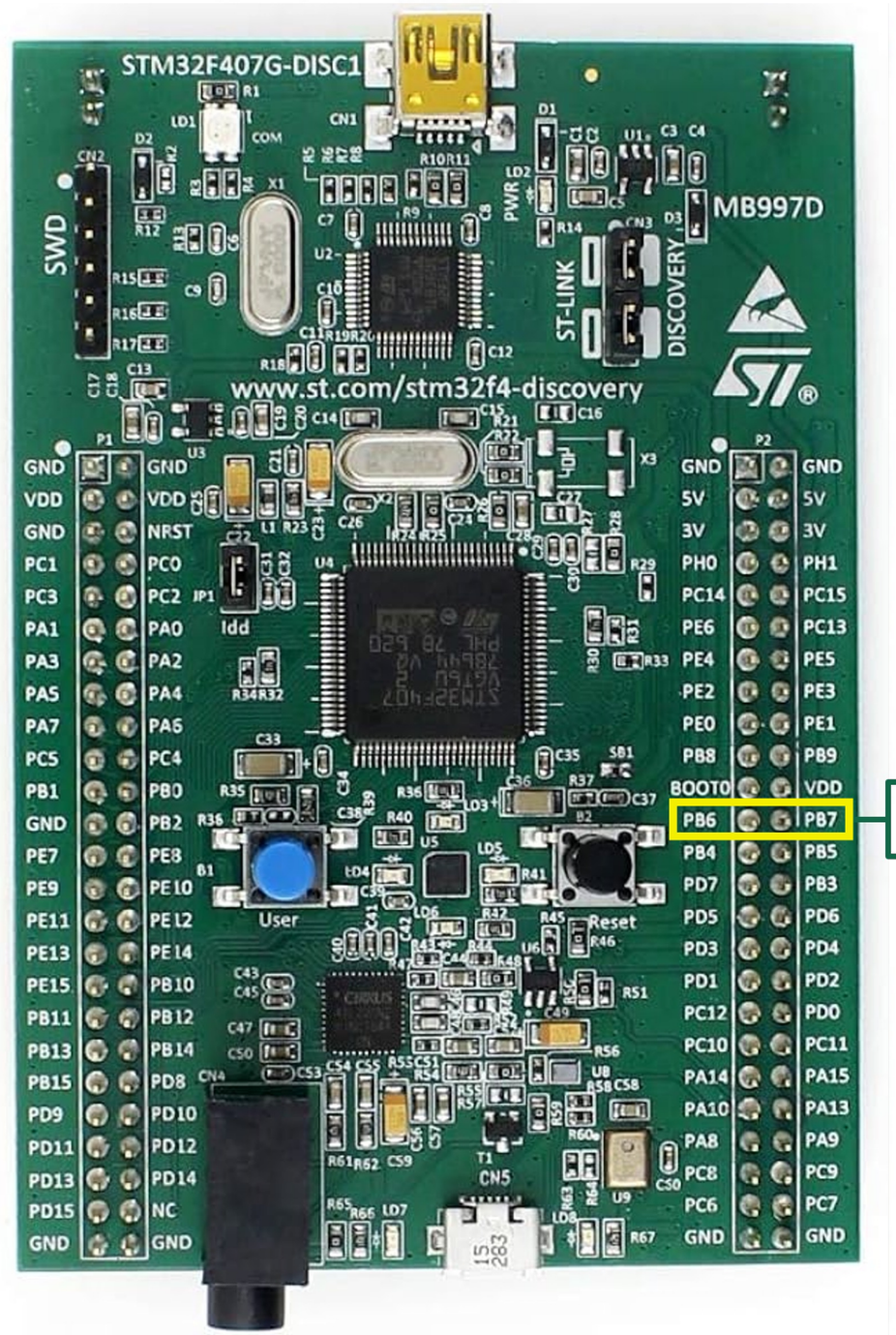
Laboratory kit





Computer board

USB ST-LINK mini-B connector

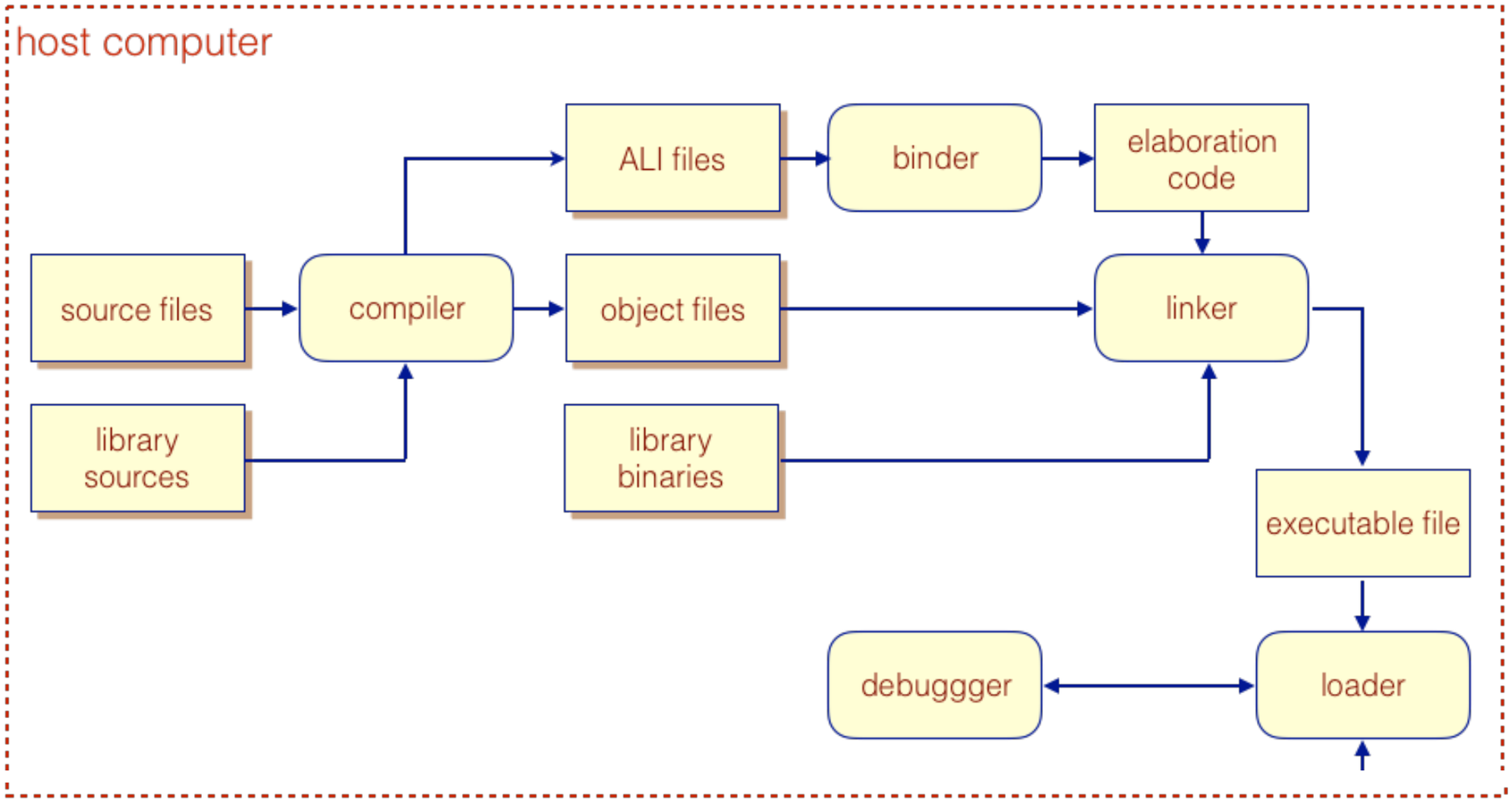


Pins PB6 & PB7

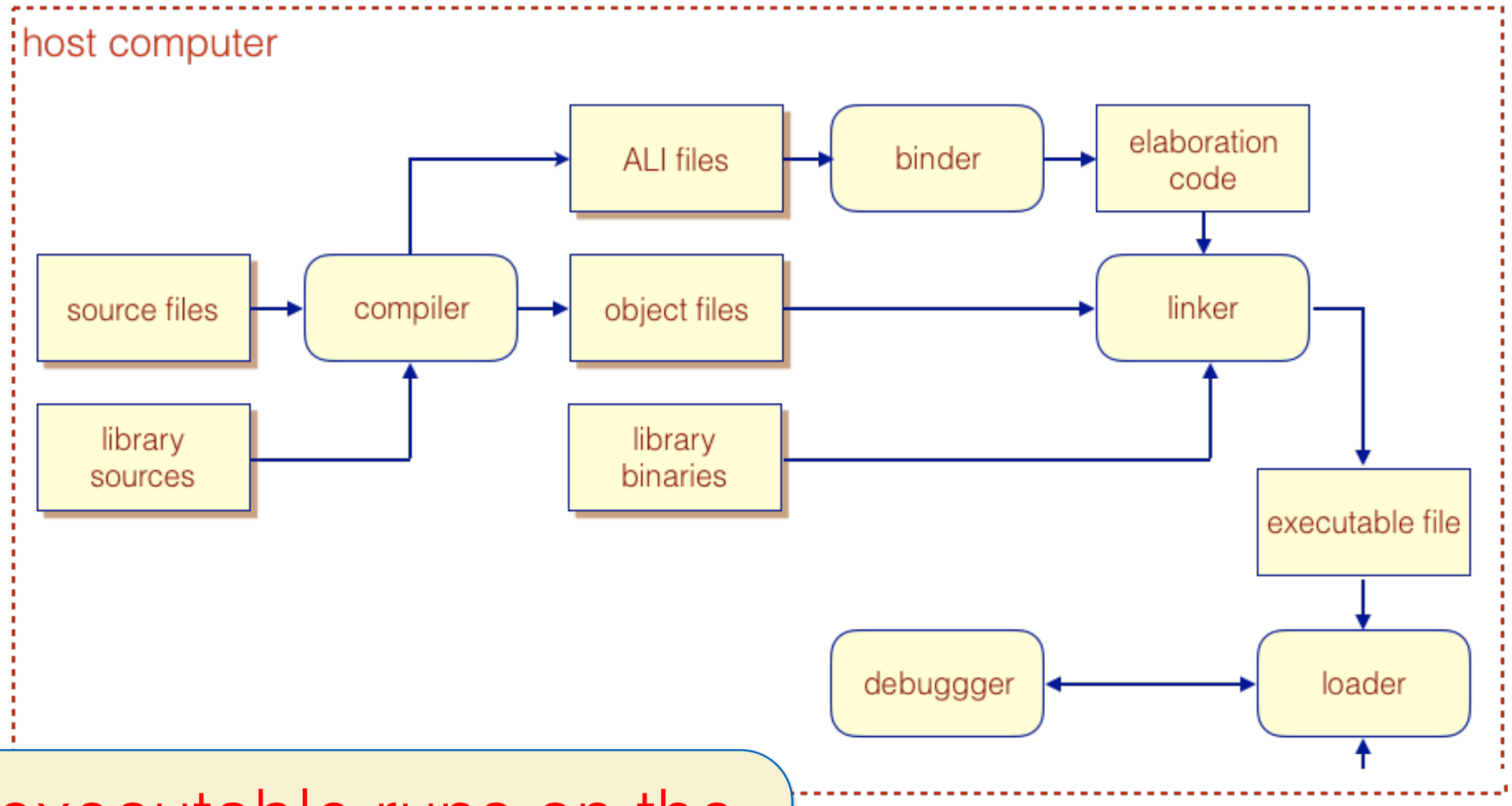
GND pin

USB OTG micro-AB connector

1. Classical development process



1. Classical development process

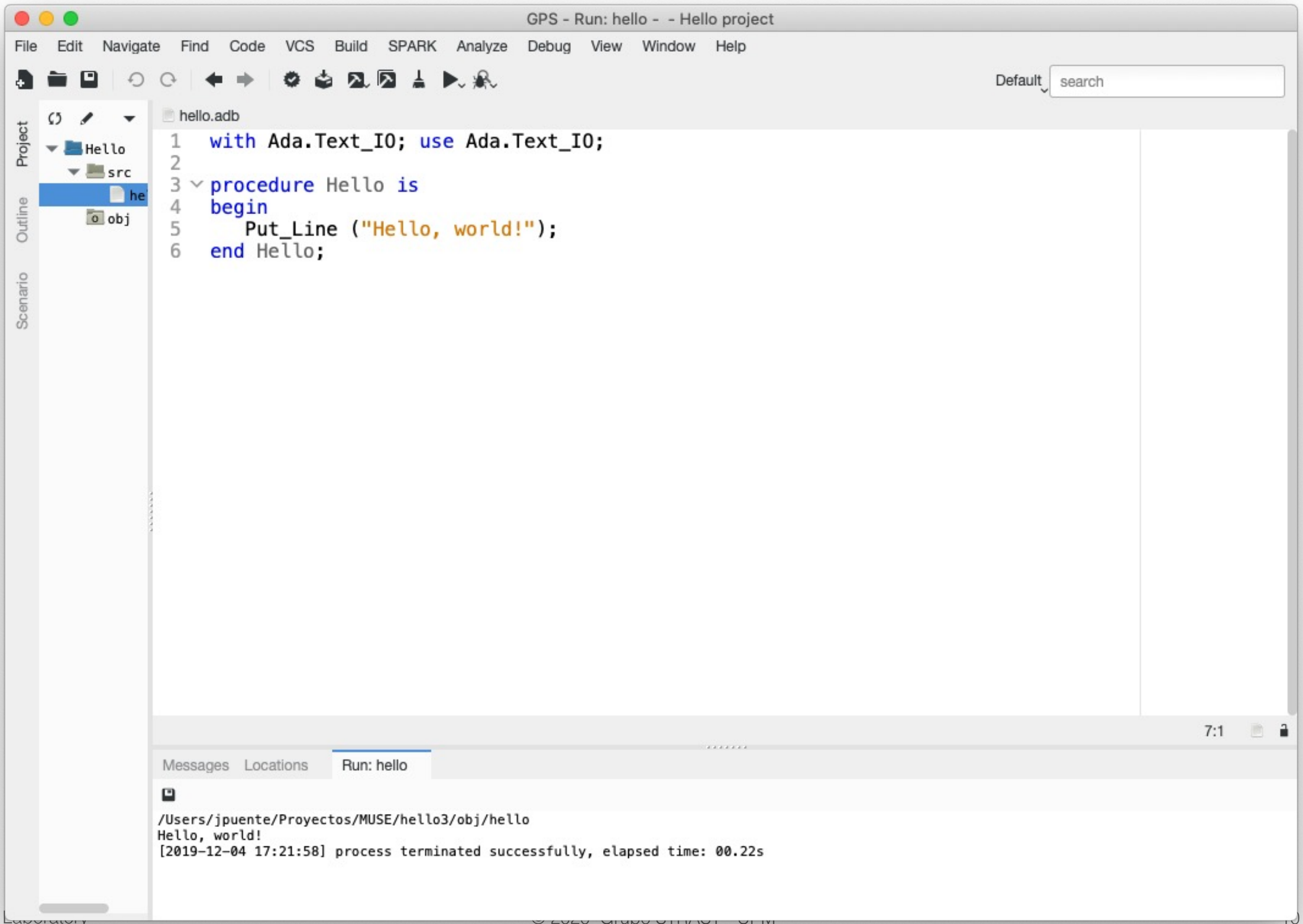


The executable runs on the host Operating System (Windows, Linux, MacOS)

1. Install the native compiler

- Windows:
  - Download and run `gnat-2020-20200429-x86_64-windows-bin.exe`
  - Run the GPS application
  - Create a new project and enter the source code for hello.adb
  - Build and run the executable
- MacOS and Linux
  - See laboratory guide

Sample screenshot



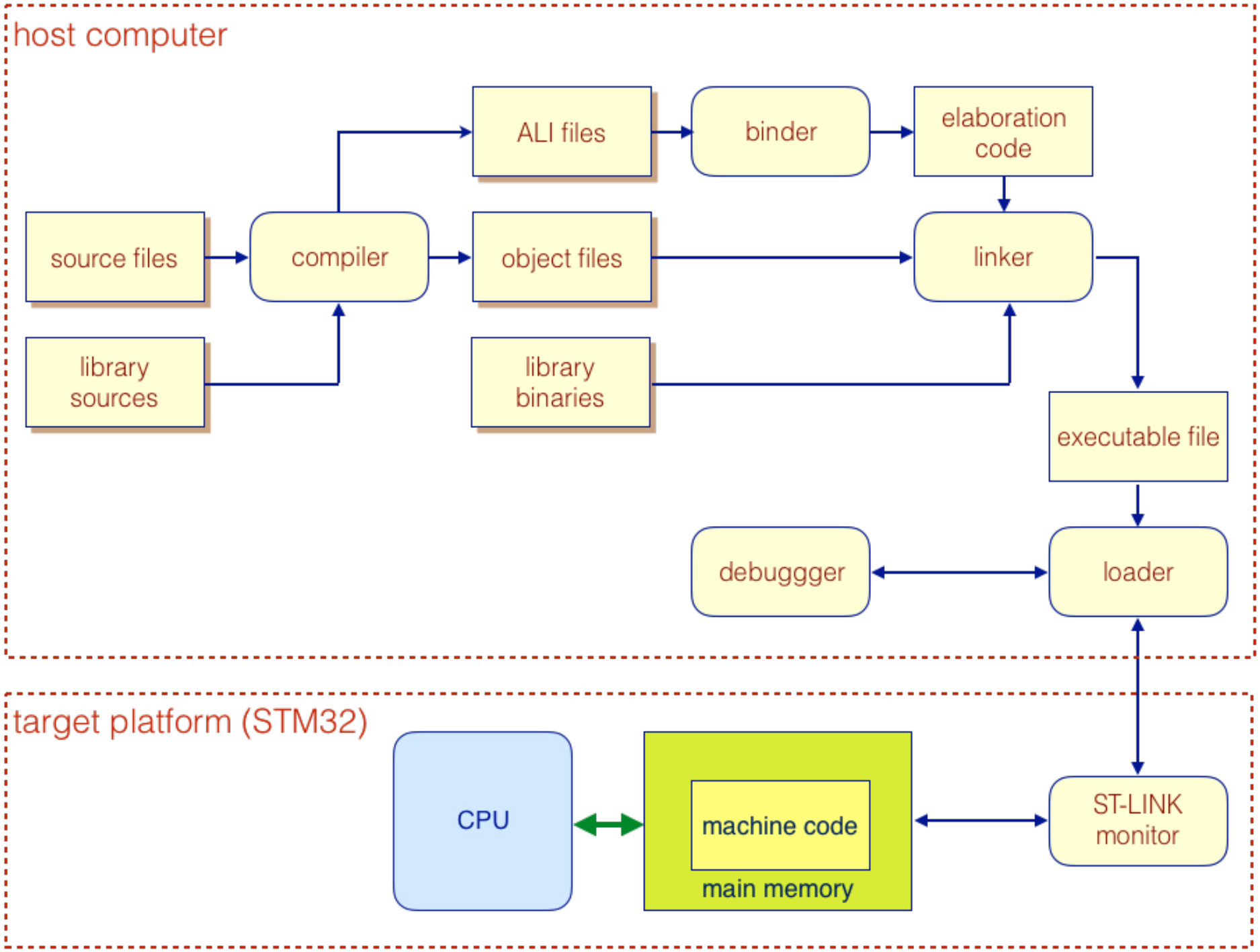
2a. Install cross compiler for STM32F4

- Windows:
  - Download and execute the cross-compiler

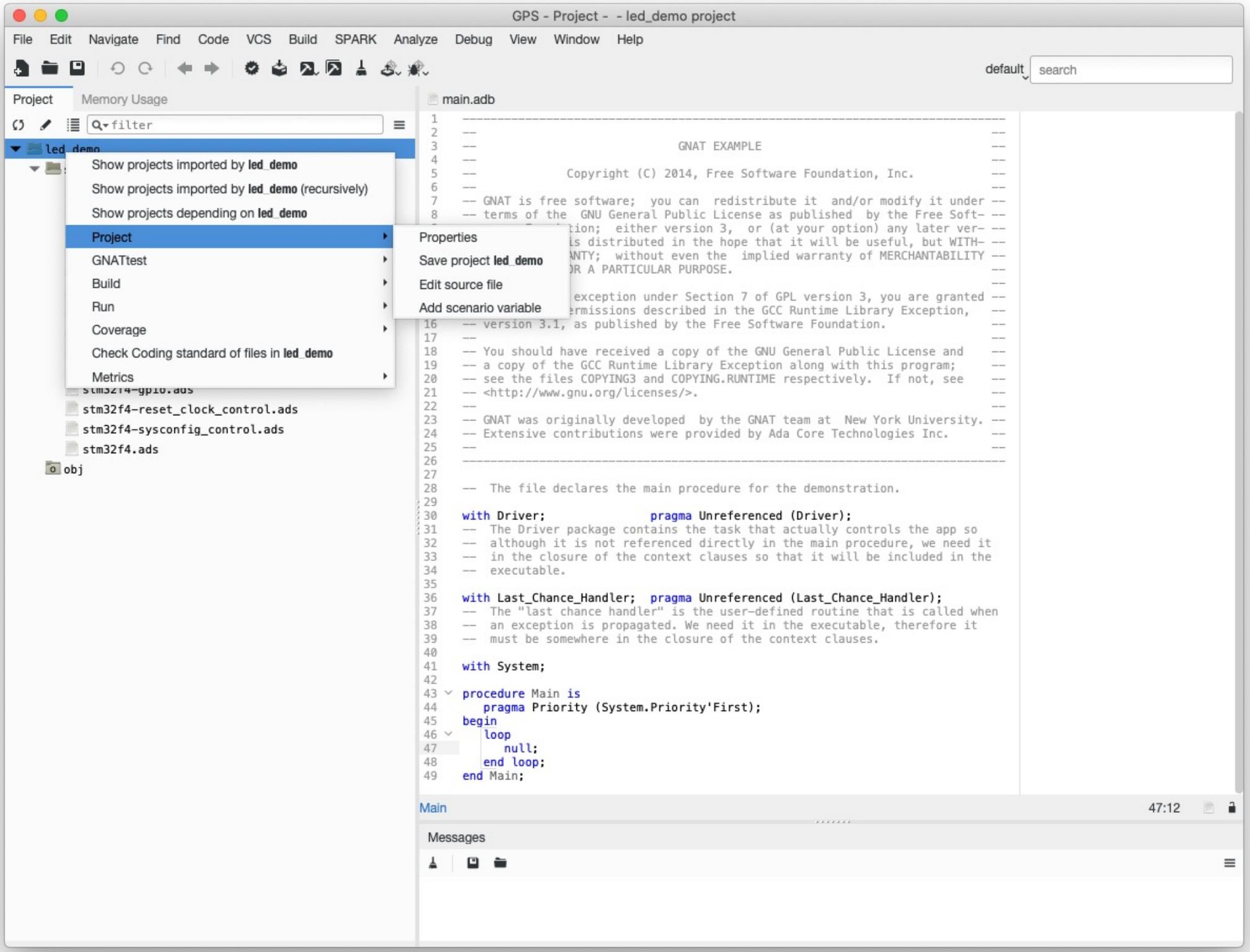
`gnat-2020-20200429-arm-elf-windows64-bin.exe`

  - Download and execute the ST-LINK driver
    - follow the instructions in `readme.txt`
  - Start the GPS application
  - Create a new project
    - `File > New Project > STM324F compatible > LED demo project template`
    - Set `Project > Properties > Embedded > Connection tool` to `st-util`
  - Build and run the executable
  - Connect the board to the host computer and flash the executable to the board

Cross-compilation tools



Sample screenshot



2b. Install the Ada Drivers Library

- All platforms:
  - Download zip file from

https://github.com/AdaCore/Ada_Drivers_Library

  - Unzip the archive and move the resulting folder to your laboratory folder
  - Rename the folder to `Ada_Drivers_Library`
  - Open project

`…/Ada_Drivers_Library/examples/STMF4_DISCO/blinky_f4disco.gpr.`

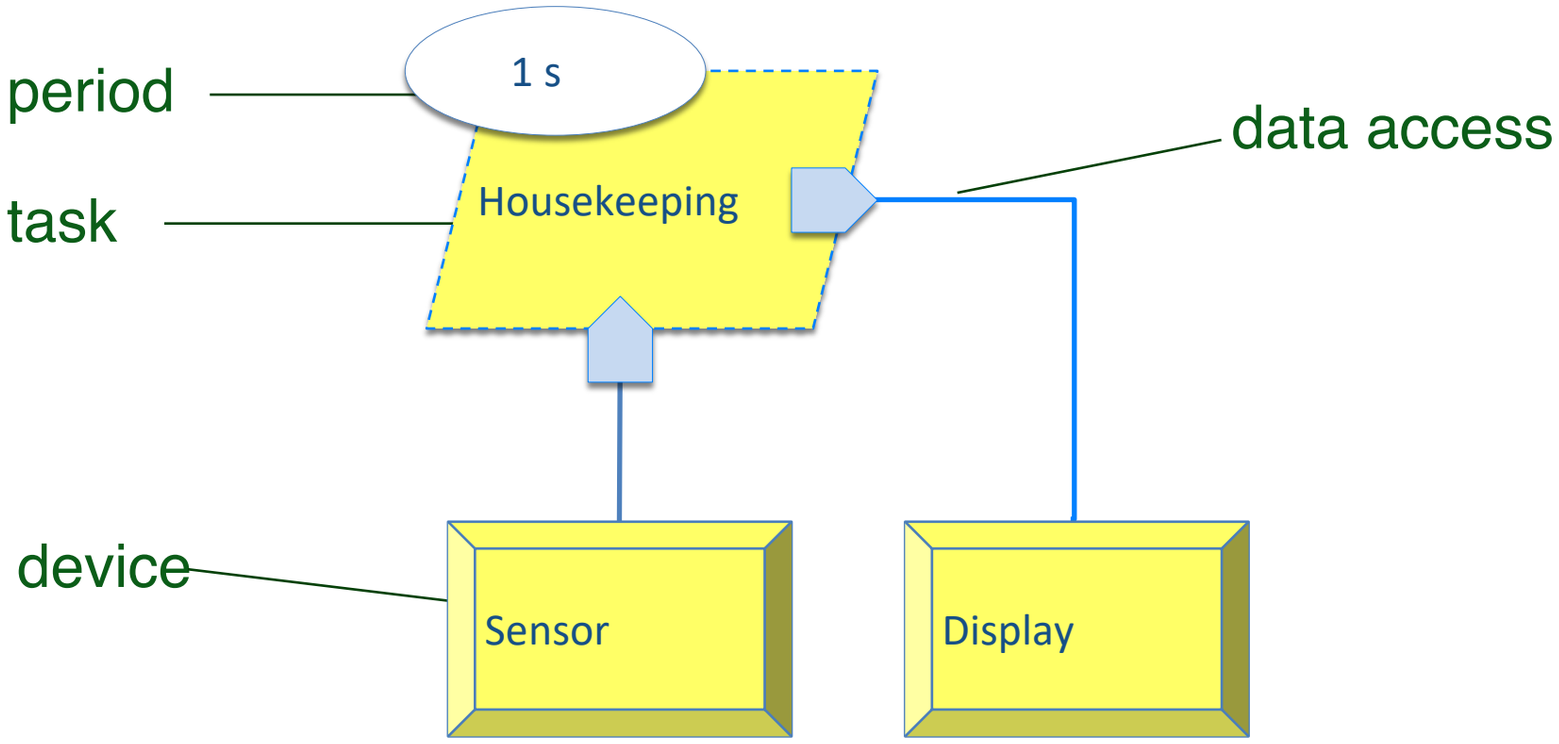
  - Build the executable and flash it to the board

3. Simple housekeeping system

- Read a single sensor (OBC_T) and show the reading on the screen
  - the OBC board has no screen
    - use the debugger (for now) - *semi-hosting*
  - use the Ada Drivers Library (ADL) to read the sensor
    - STM32.Device
    - STM32.ADC

Software architecture

AADL : Architecture Analysis & Design Language



AADL components implemented as Ada packages

- main procedure: OBDH
- additional packages for data definitions & others as necessary

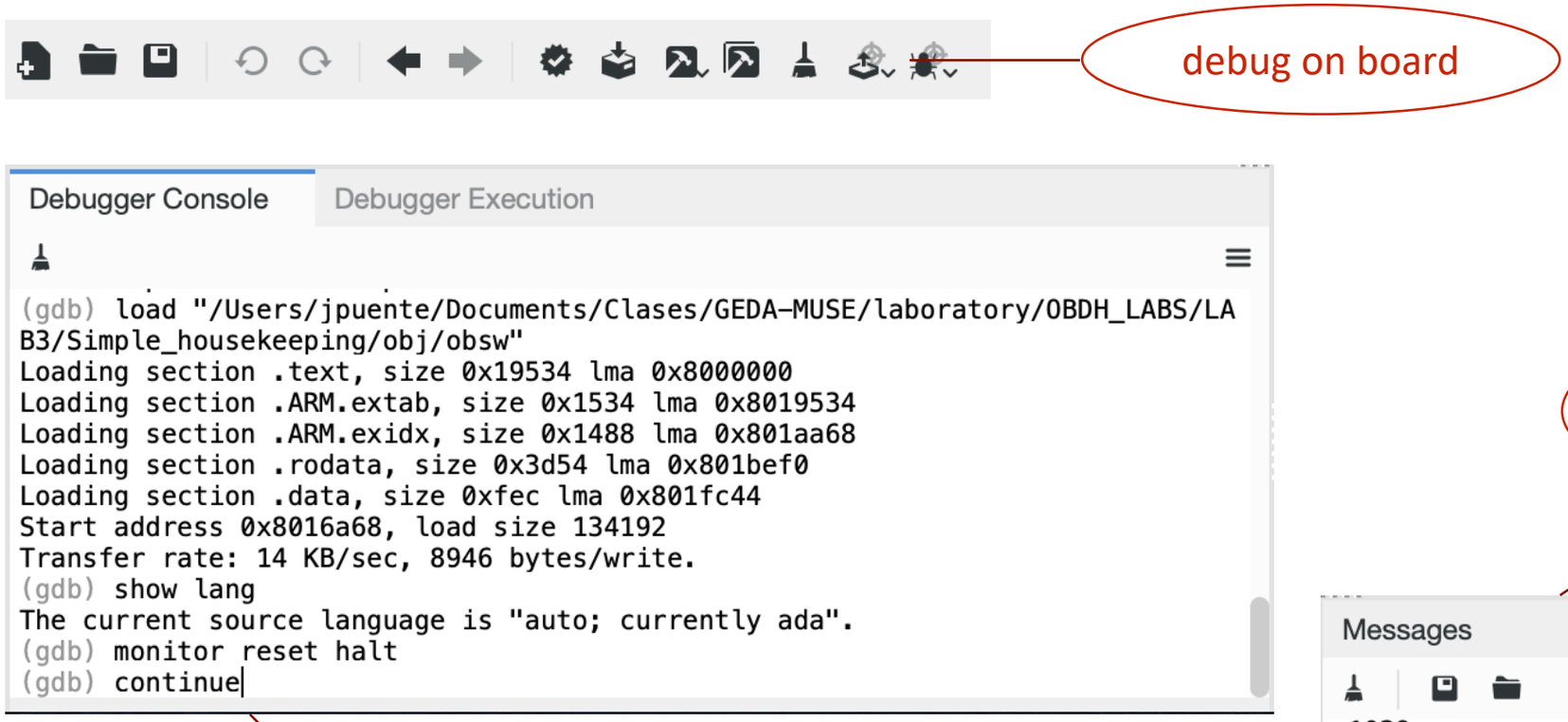
Temperature sensor

- OBC_T : MCU internal temperature sensor
  - connected to ADC1_IN16 input
  - range -40 .. +125 ºC
  - 14-bit reading VSENSE: 0 .. 4095
  - Temperature (in °C) = {(VSENSE – V25) / Avg_Slope} + 25

Symbol	Parameter	Min	Typ	Max	Unit
T_L(1)	V_{SENSE} linearity with temperature	-	±1	±2	°C
Avg_Slope(1)	Average slope	-	2.5		mV/°C
V_{25}(1)	Voltage at 25 °C	-	0.76		V
tSTART(2)	Startup time	-	6	10	µs
TS_temp(2)	ADC sampling time when reading the temperature (1 °C accuracy)	10	-	-	µs

Display

- Emulate a display with *semi-hosting*
  - run with the debugger
  - `Ada.Text_IO` output is redirected to the debugger



Study the code and make changes

- All platforms:
  - Download zip file from moodle or

https://github.com/STR-UPM/OBDH_LABS

  - Unzip the archive and move the resulting folder to your laboratory folder
  - Open project `.../LAB3/Simple_housekeeping/simple_housekeeping.gpr`
  - Build the executable and debug on the board

Additional tasks

- Include the conversion to Celsius in the `Display.Put` procedure.
- Add the following statement to the main loop in the `Housekeeping Run` procedure:

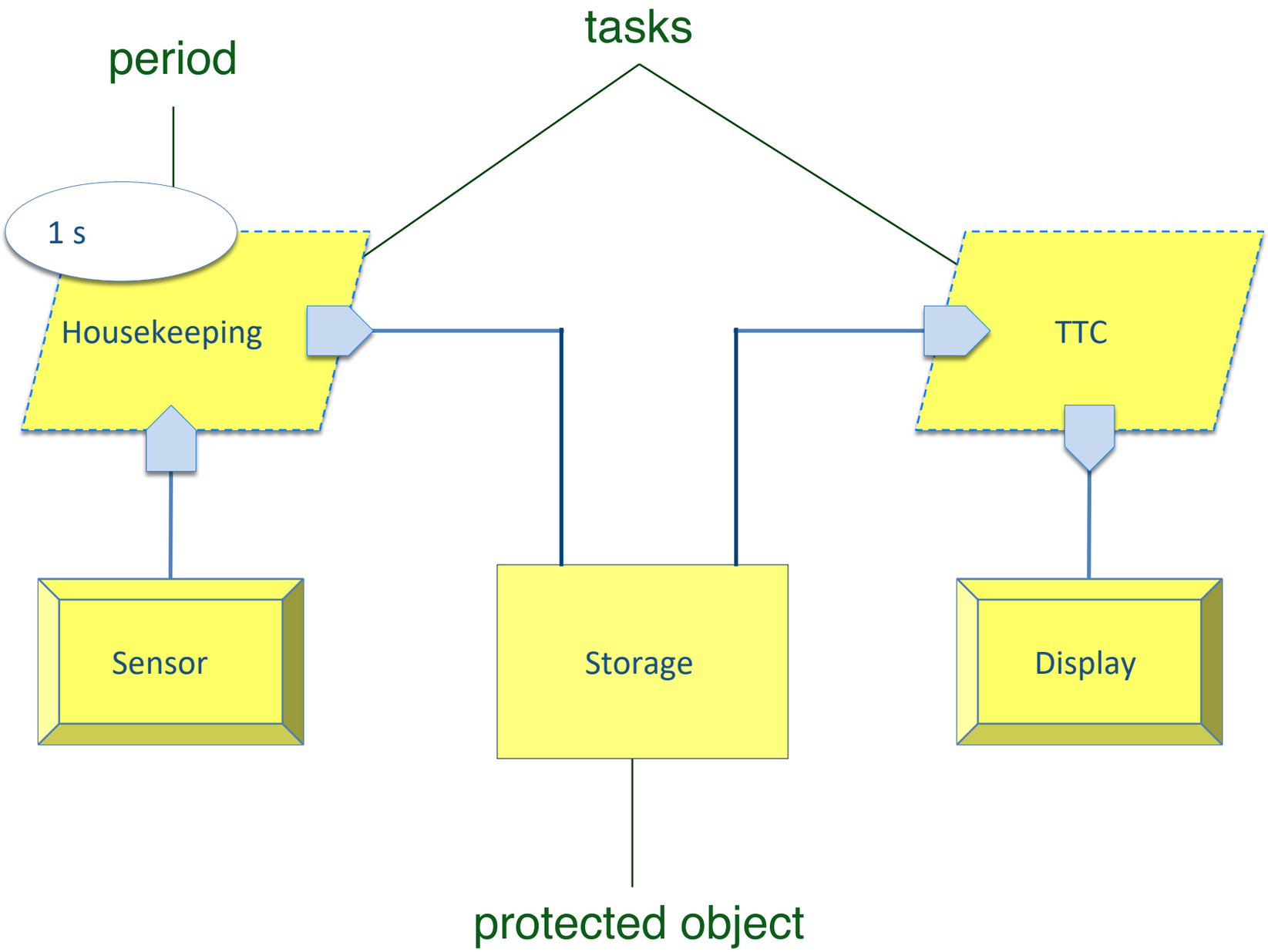
```
delay until Clock + Milliseconds (1000);
```

(see the code in the Blinky_LEDS program)

4. Tasking housekeeping system

- Add two tasks for better structuring
  - Housekeeping
    - read a sensor (OBC_T)
  - TTC
    - display the sensor value
- Add a protected object for inter-task communication
  - Storage
    - the housekeeping task puts the sensor value in the storage
    - the TTC task gets the value from the storage

Software architecture



Study the code and make changes

- All platforms:
  - Download zip file from moodle or

https://github.com/STR-UPM/OBDH_LABS

  - Unzip the archive and move the resulting folder to your laboratory folder
  - Open project `.../LAB4/Tasking_housekeeping/tasking_housekeeping.gpr`
  - Build the executable and debug on the board

Additional tasks

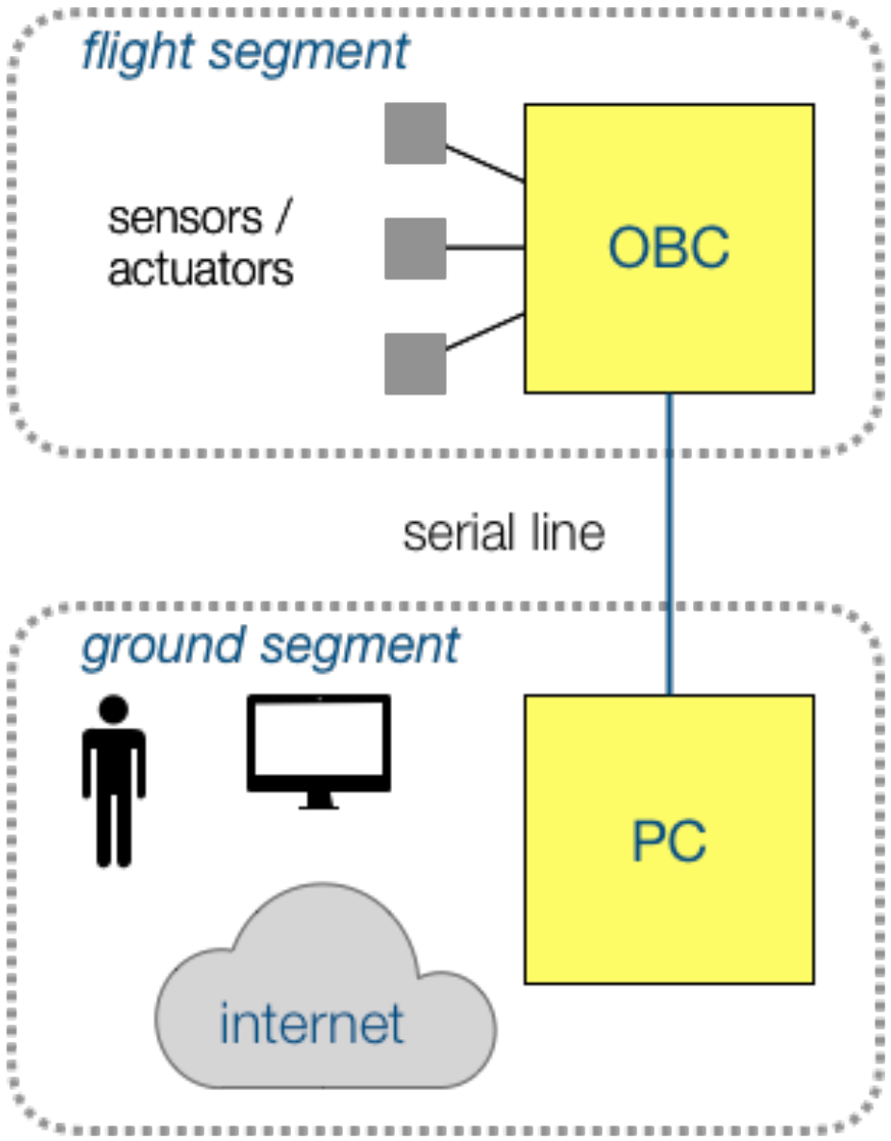
- Include the conversion to Celsius in the `Display.Put` procedure.
- Add the following statement to the main loop in the `Housekeeping Run` procedure:

```
delay until Clock + Milliseconds (1000);
```

(see the code in the Blinky_LEDS program)

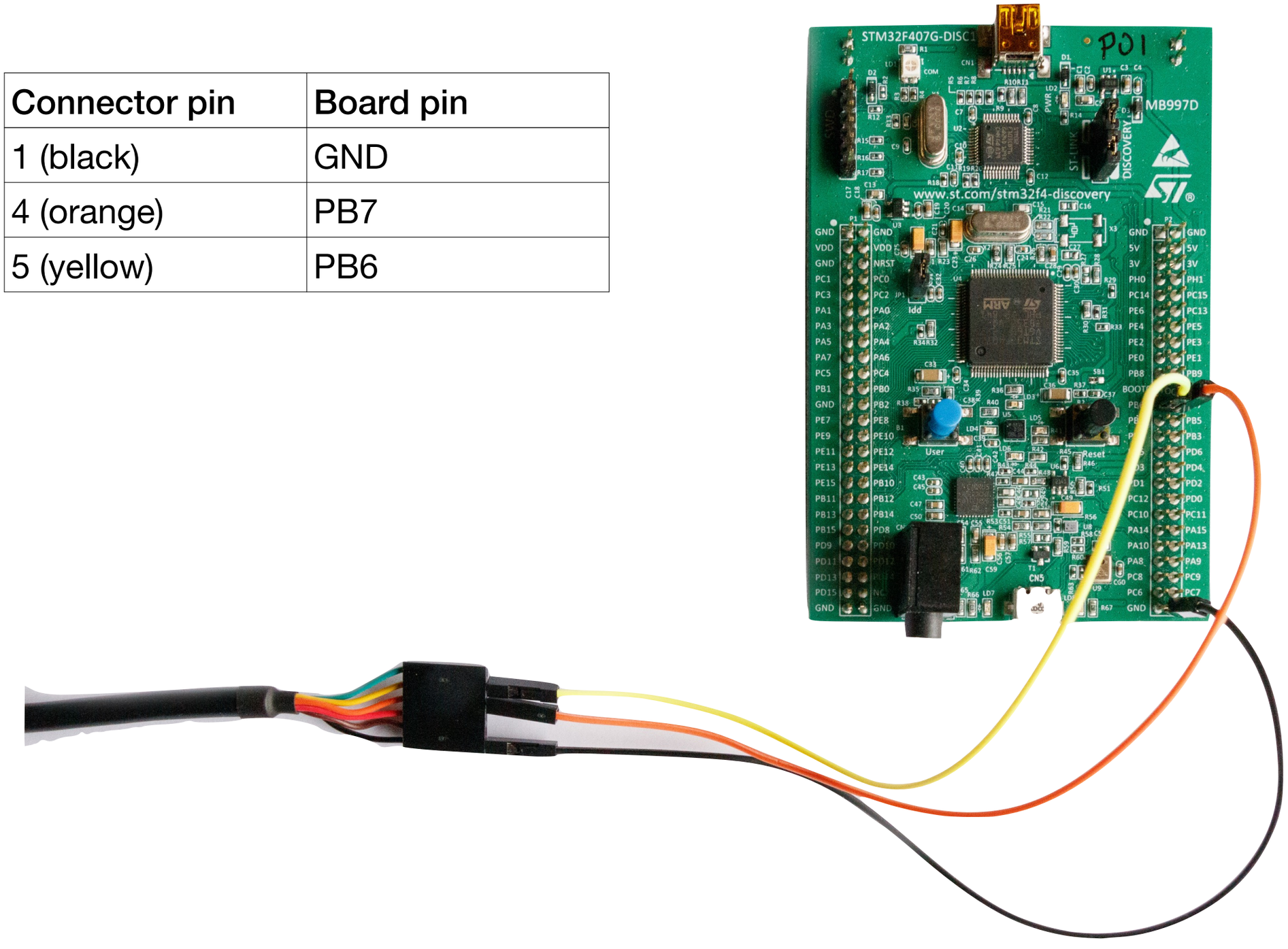
5. Distributed housekeeping system

- Add a serial interface connected to the host PC
  - simulate a radio link between flight and ground systems



Hardware

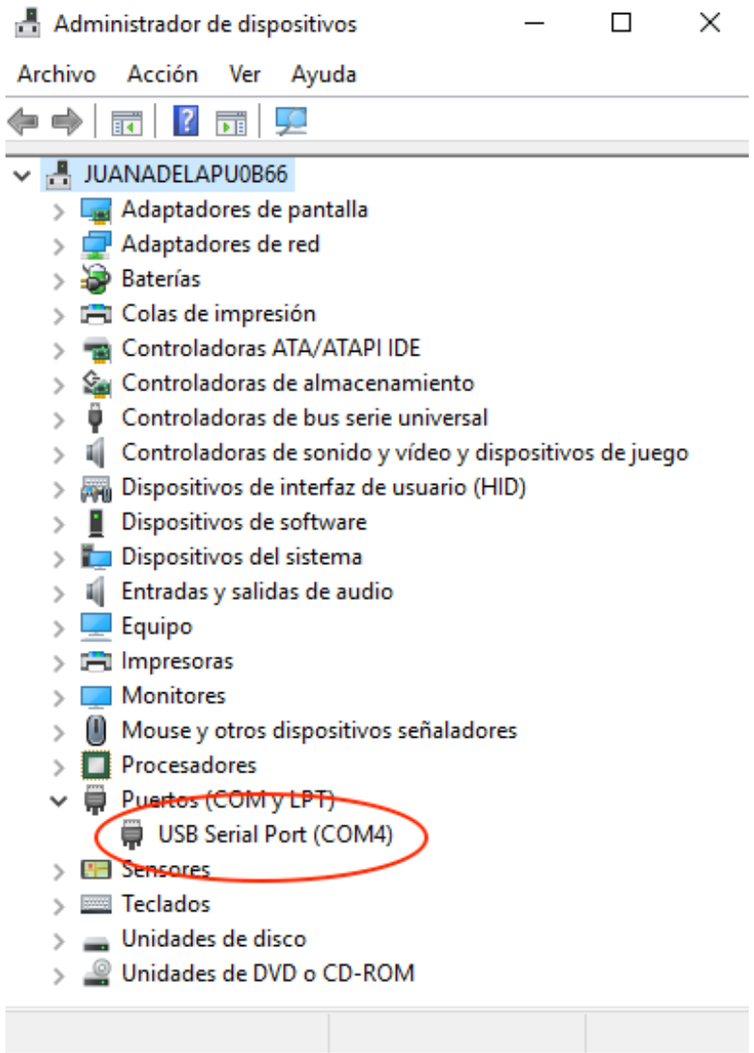
Connector pin	Board pin
1 (black)	GND
4 (orange)	PB7
5 (yellow)	PB6

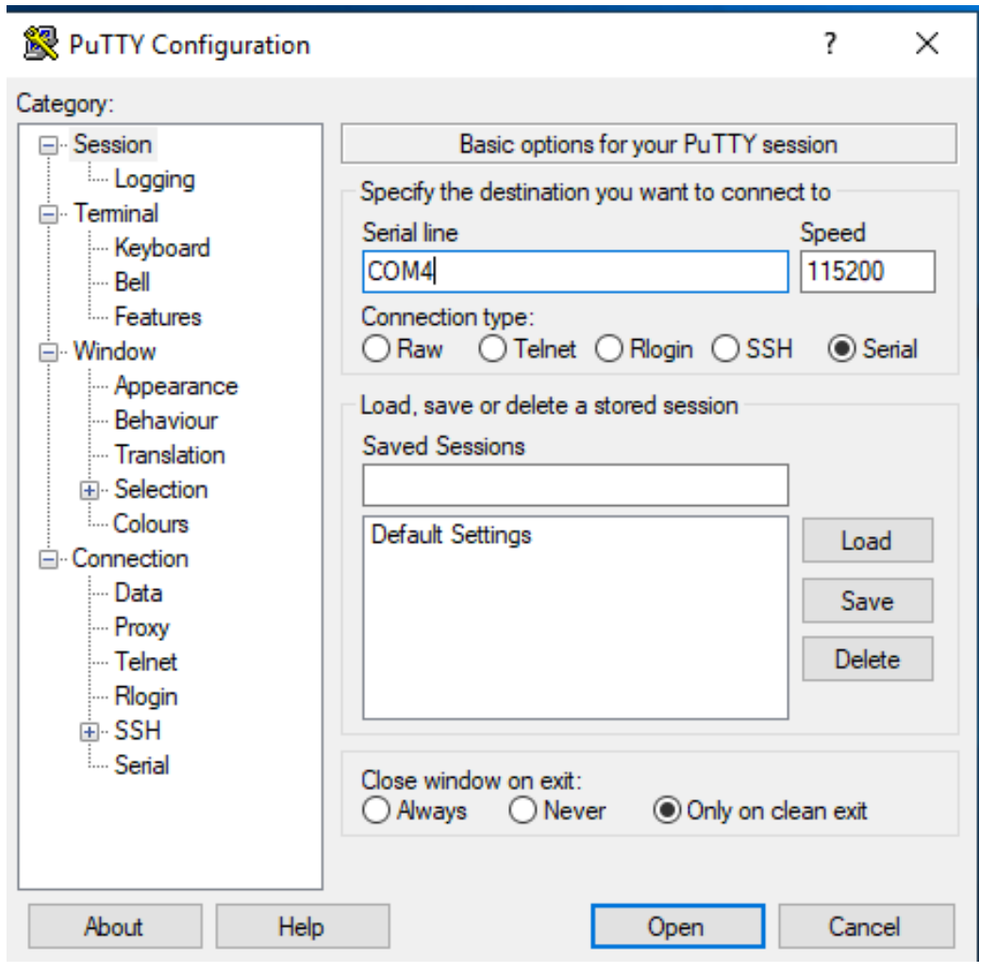


Host terminal

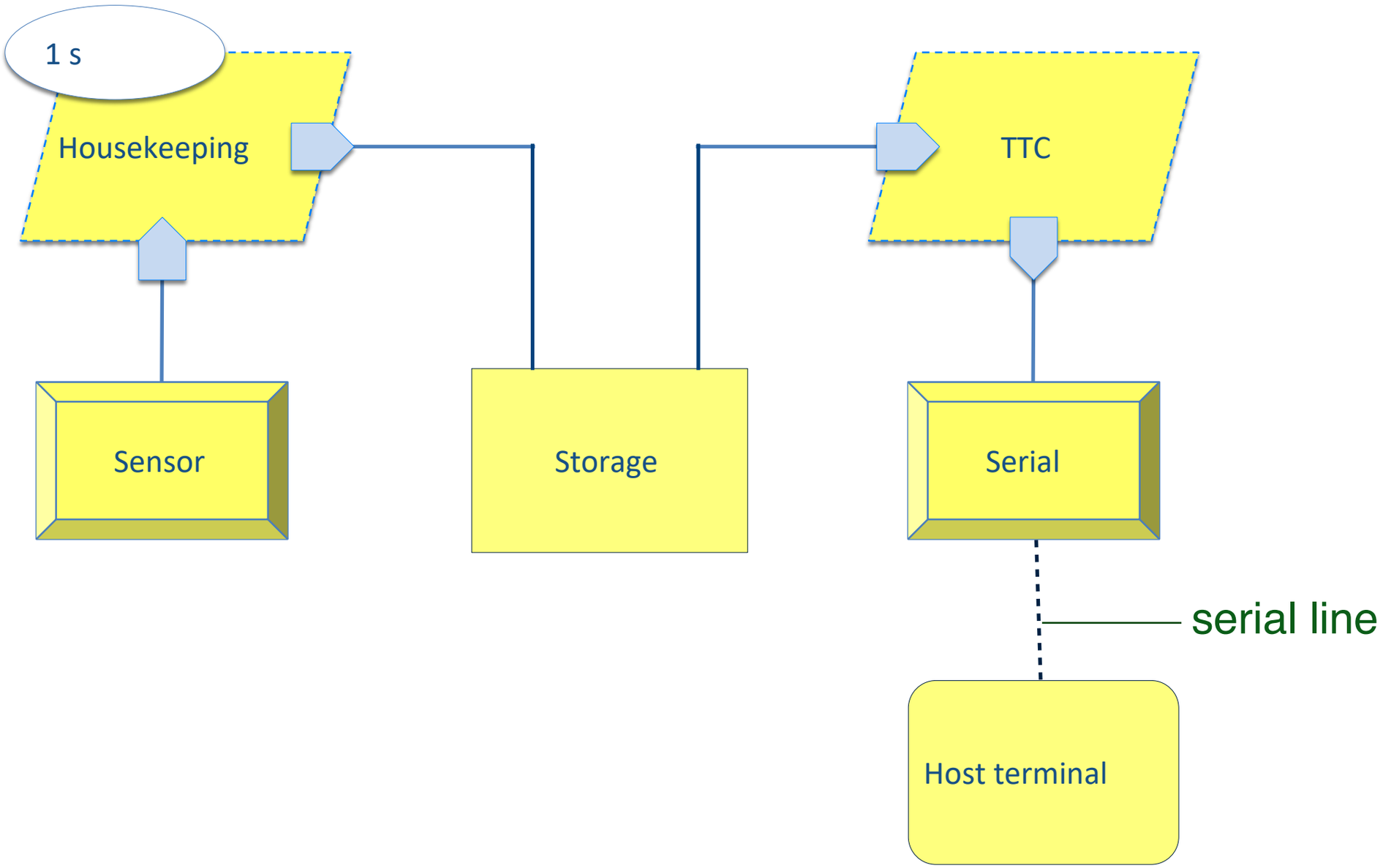
(Windows — for other platforms see manual)

- Download and install https://www.putty.org
- Find the COM port in device manager (e.g. COM4)
- Open PutTTY and configure as serial connection,115200 bps, 8N1





Software architecture



Study the code and make changes

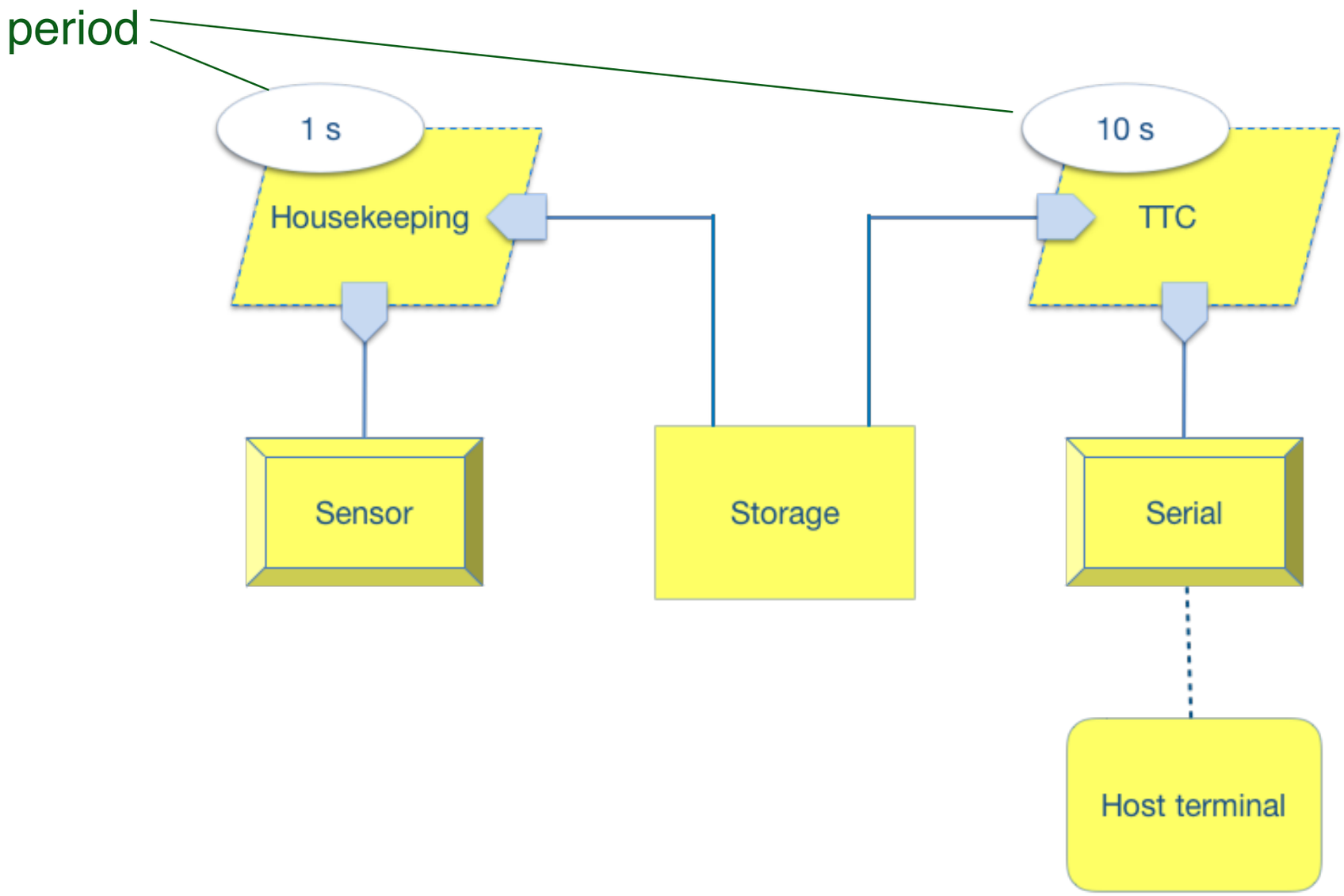
- All platforms:
  - Download zip file from moodle or

https://github.com/STR-UPM/OBDH_LABS

  - Unzip the archive and move the resulting folder to your laboratory folder
  - Open project
    …/LAB5/Distributed_housekeeping/distributed_housekeeping.gpr
  - Build the executable and flash to board

6. Real-time housekeeping system

- Add real-time requirements and priorities to tasks
- Add timestamps to measurements



Real-time requirements

Task	Period	Deadline	Priority
Housekeeping	1,0	1,0	20
TTC	10,0	2,0	10
Storage Buffer	—	—	20

```
package Housekeeping is
   Period      : Time_Span := Milliseconds (1000);  -- 1s
   HK_Priority : constant System.Priority := 20;
   ...
private
   Start_Delay : Time_Span := Milliseconds (1000); -- 1s
   task Housekeeping_Task
     with Priority => HK_Priority;
end Housekeeping;
```

Implementation

```
task body Housekeeping_Task is
   Data      : State;
   Next_Time : Time := Clock + Start_Delay;
begin
   loop
      delay until Next_Time;
      ...
      Next_Time := Next_Time + Period;
   end loop;
end Housekeeping_Task;
```

Timestamps

```
package Housekeeping_Data is
   ...
   type Mission_Time is new Uint64;
   --  Seconds since system startup

   type State is
      record
         Data      : Analog_Data;
         Timestamp : Mission_Time;
      end record;

end Housekeeping_Data;
```

Housekeeping

```
procedure Get (S : out State) is
    OBC_T : Analog_Data;
    SC    : Seconds_Count;
    TS    : Time_Span;
 begin
    Sensor.Get (OBC_T);
    Split (Clock, SC, TS);
    S.Data := OBC_T;
    S.Timestamp := Mission_Time (SC);
end Get;
```

Storage

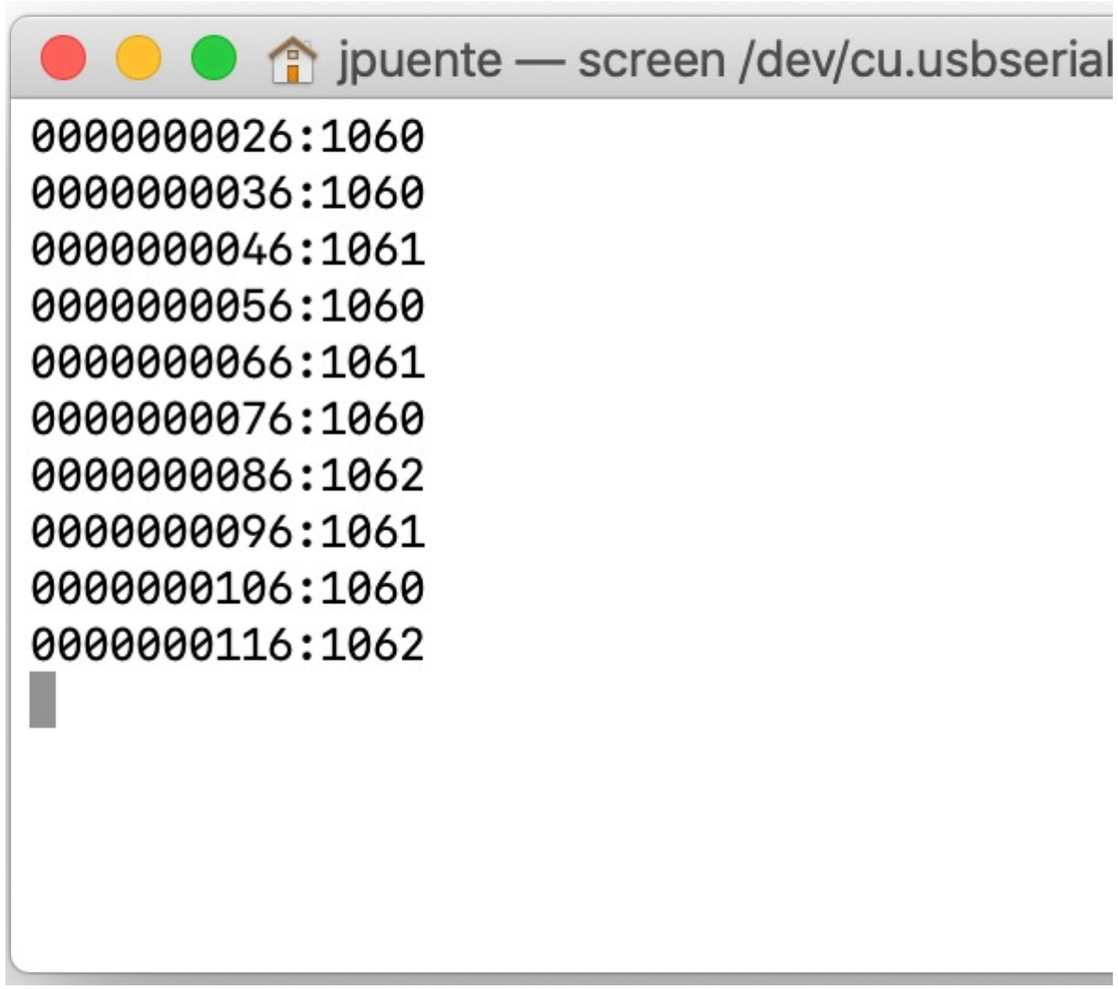
```
package Storage is

   procedure Put (Data : State);
   procedure Get (Data : out State);
   ...
   -- Real-time attributes
   ST_Priority : constant System.Priority := 20;

private

   protected Buffer
     with Priority => ST_Priority
   is ...
...
end Storage;
```

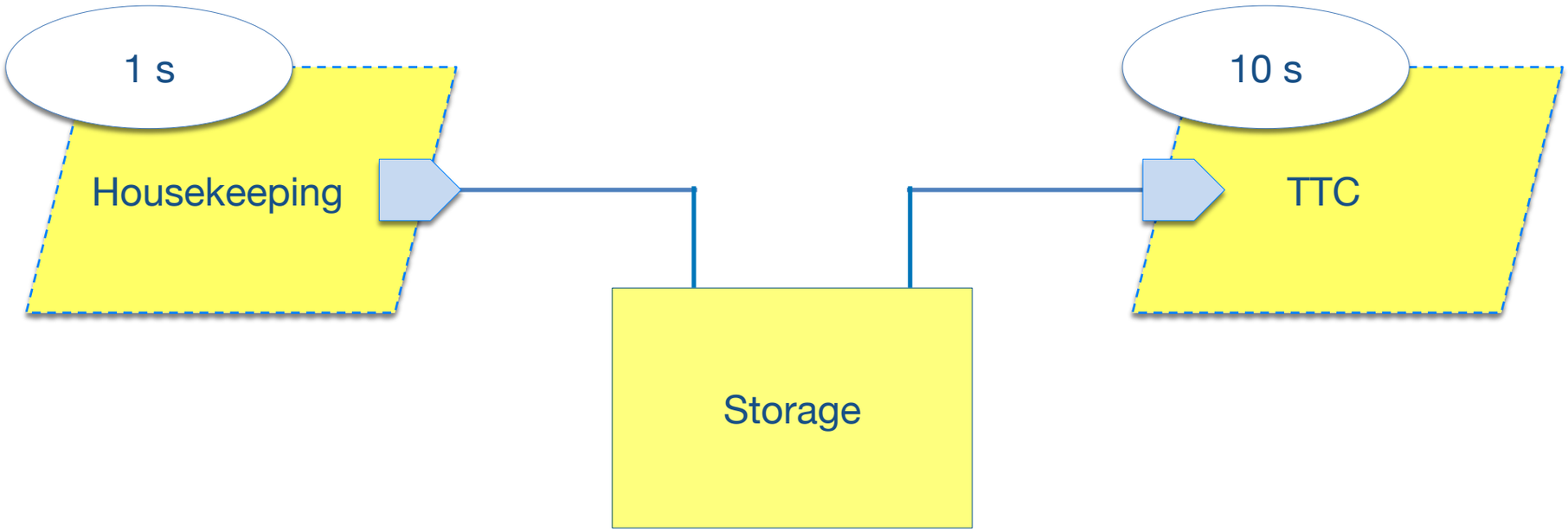
Laboratory work



- Open project `.../LAB6/RT_housekeeping/real_time_housekeeping.gpr`
- Build the executable and flash to board
- Make sure the TTY cable is connected
- Telemetry messages appear on the ground terminal

Real-time analysis

- Task structure



- Real-time attributes

Task	T	C	B	D	R	P	C_{Put}	C_{Get}
HK	1,0			1,0		20		
TTC	10,0			2,0		10		
						CP	20	20

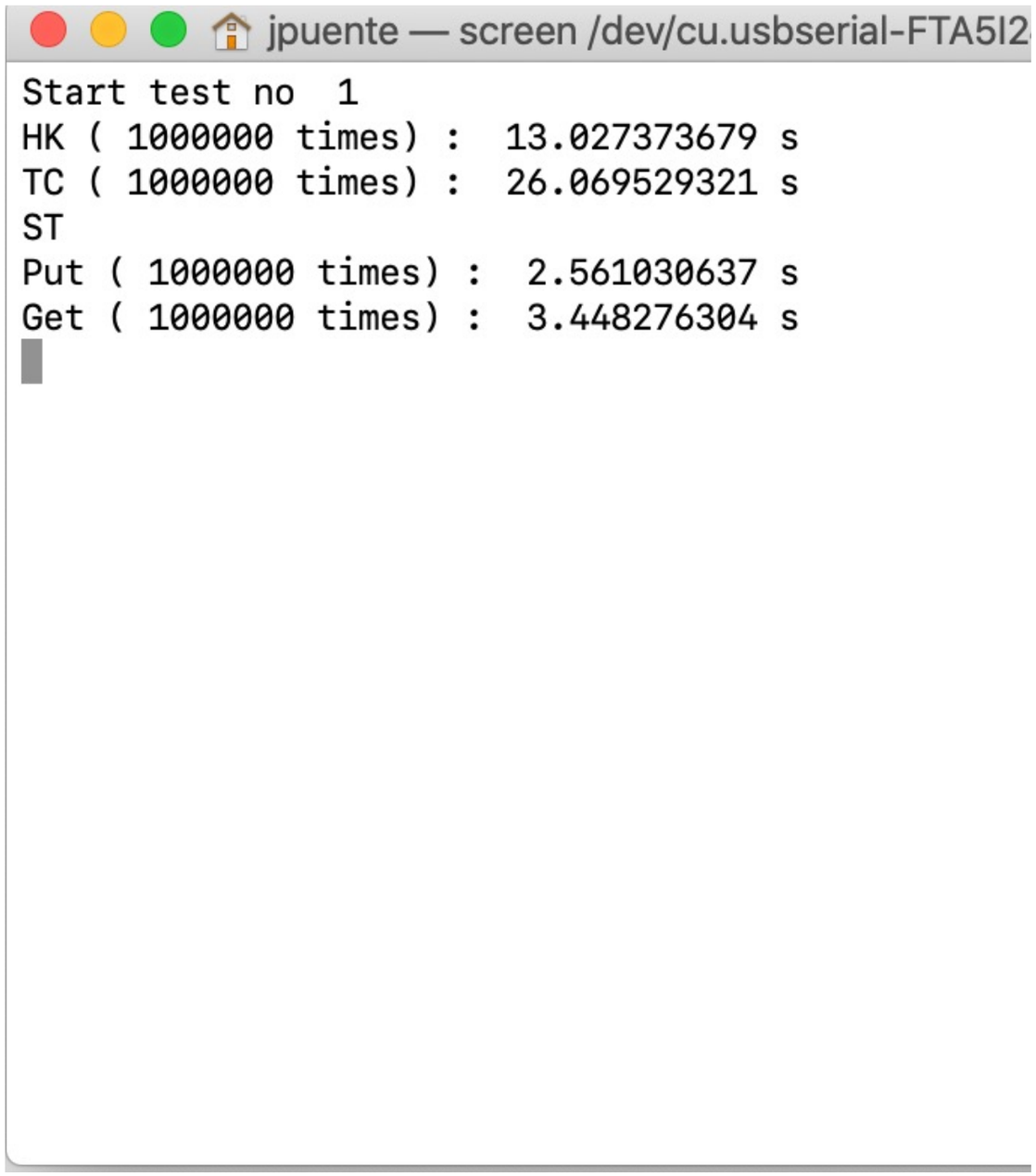
WCET measurement

- A simple dynamic measurement technique will be used in the laboratory
- Execute task bodies a number of times and measure times with the board real-time clock
  - e.g. for HK task

```
T1 := Clock;
for I in 1..N loop
   Get(Data);
   Storage.Put (Data);
   T := T + Period;
end loop;
T2 := Clock;
C := T2 - T1;
```

  - the estimated WCET in seconds is C/N

Laboratory work



- Open project `.../LAB6/RT_housekeeping/wcet_meter.gpr`
- Study the source code
- Build the executable and flash to board
- Make sure the TTY cable is connected
- Analysis results appear on the ground terminal

Real-time analysis with measured values

Task	T	C	B	D	R	P	C_{Put}	C_{Get}
HK	1,0	$13 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	1,0		20	$3 \cdot 10^{-6}$	—
TTC	10,0	$26 \cdot 10^{-6}$	—	2,0		10	—	$4 \cdot 10^{-6}$
						CP	20	20

$$R_i = C_i + B_i + \sum_{j \in \mathrm{hp}(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

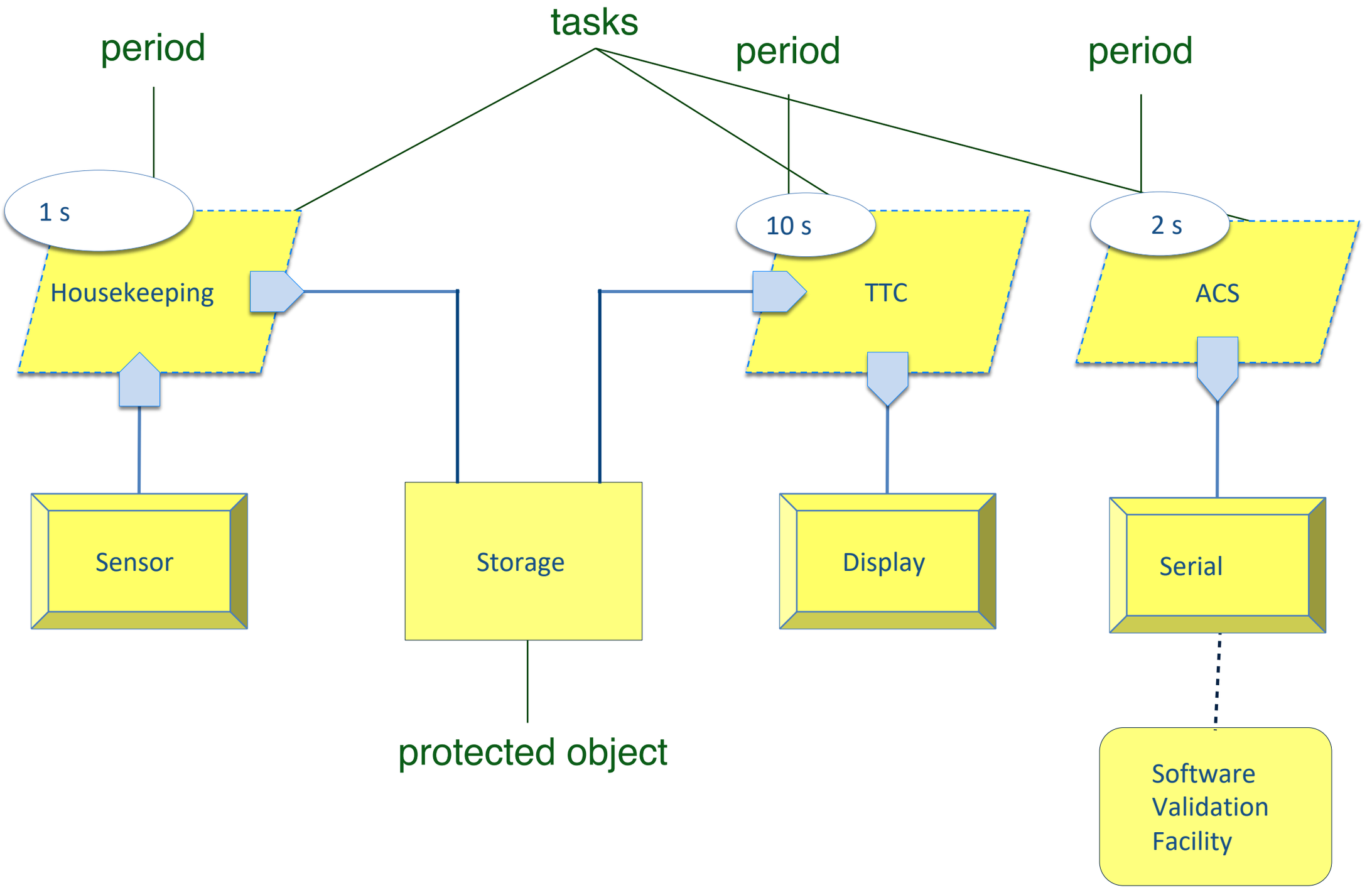
Task	T	C	B	D	R	P	C_{Put}	C_{Get}
HK	1,0	$13 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	1,0	$17 \cdot 10^{-6}$	20	$3 \cdot 10^{-6}$	—
TTC	10,0	$26 \cdot 10^{-6}$	—	2,0	$39 \cdot 10^{-6}$	10	—	$4 \cdot 10^{-6}$
						CP	20	20

All deadlines are guaranteed

7. Real-time housekeeping with ACS

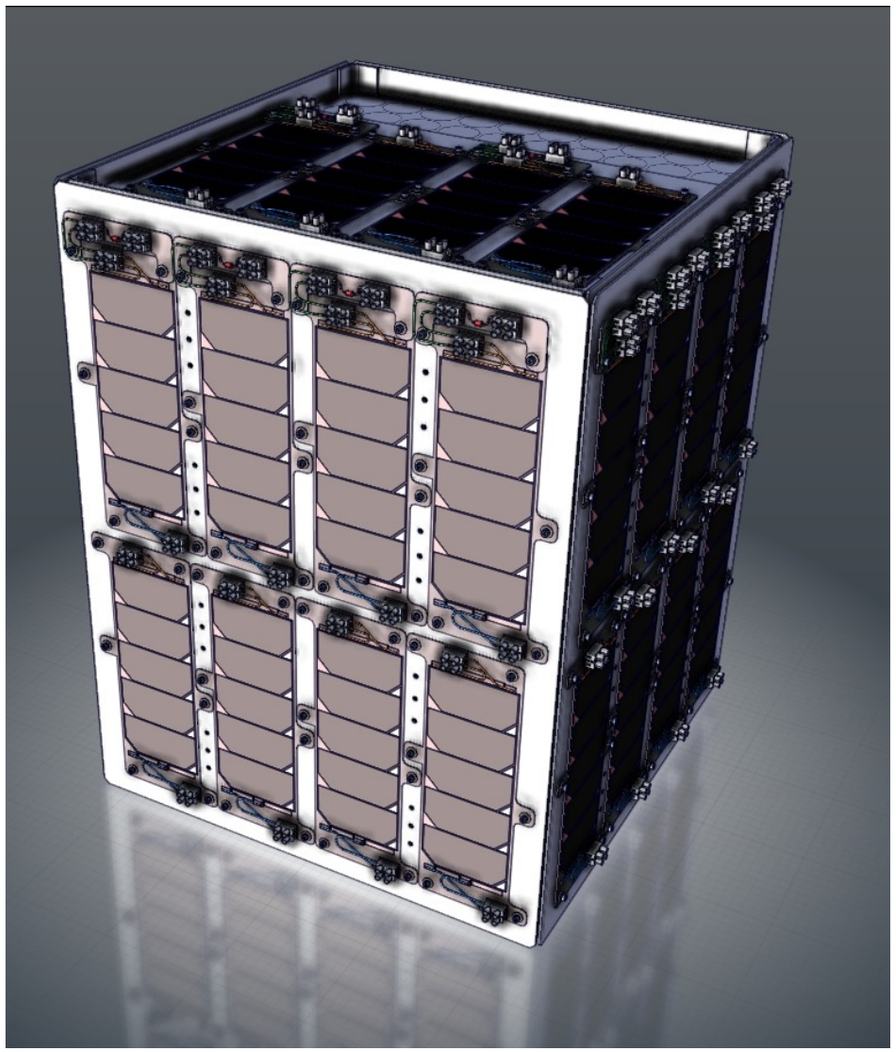
- Include three tasks:
  - Housekeeping
    - read a sensor (OBC_T)
  - TTC
    - display the sensor value using semi-hosting
  - ACS
    - control the attitude of the satellite
- Host computer runs Simulink model of the environment
  - Host and target interchange sensor readings and actuator outputs by serial line

Software architecture



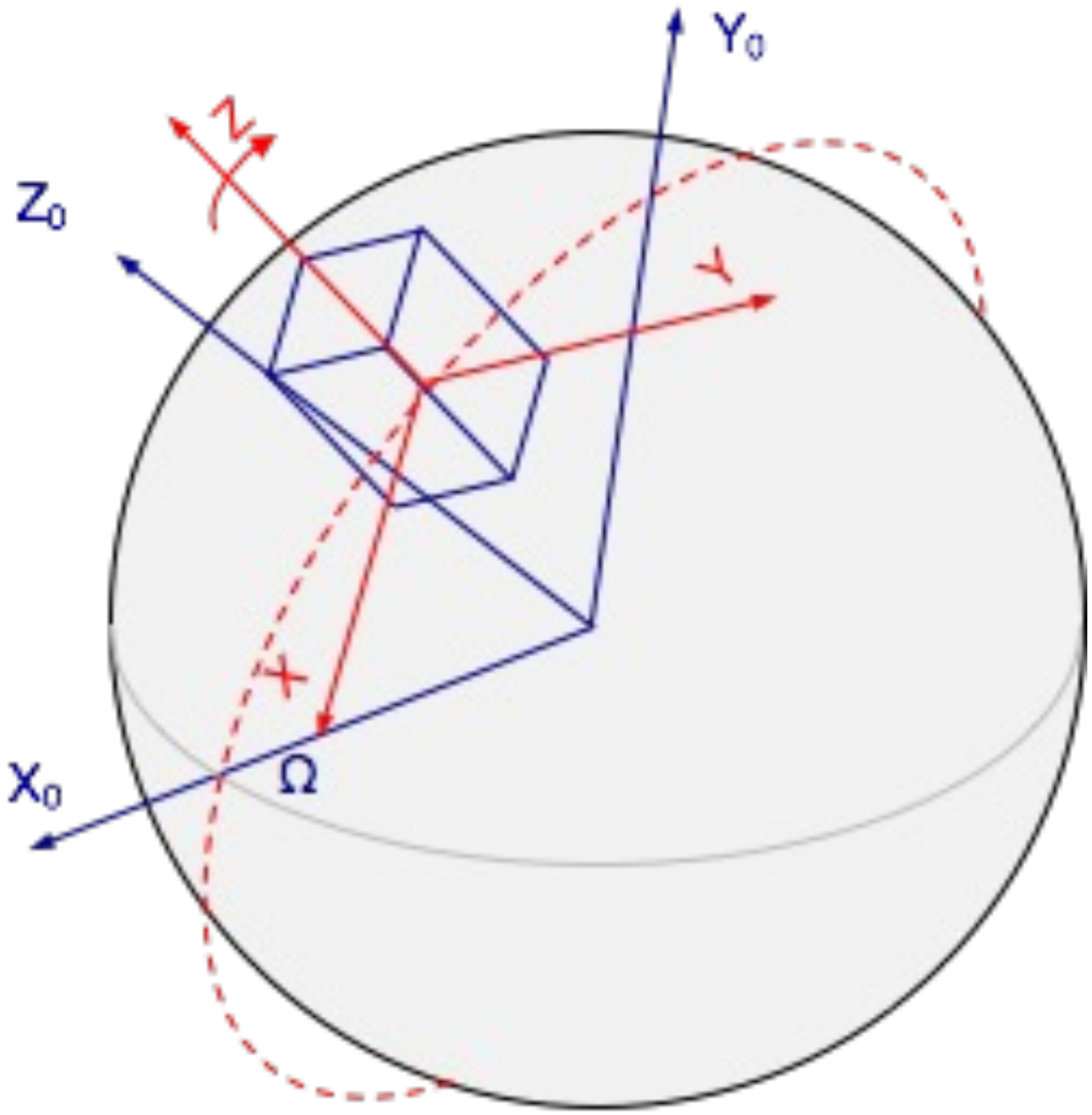
UPMSat-2

- Experimental micro-satellite
  - 0.50 × 0.50 × 0.60 m, 50 kg
  - sun-synchronous orbit
    - 700 km, 98 min period
  - powered by solar panels
  - VHF radio dual link 400 MHz
- Dipole antenna on top face
  - must be visible from Earth at all times

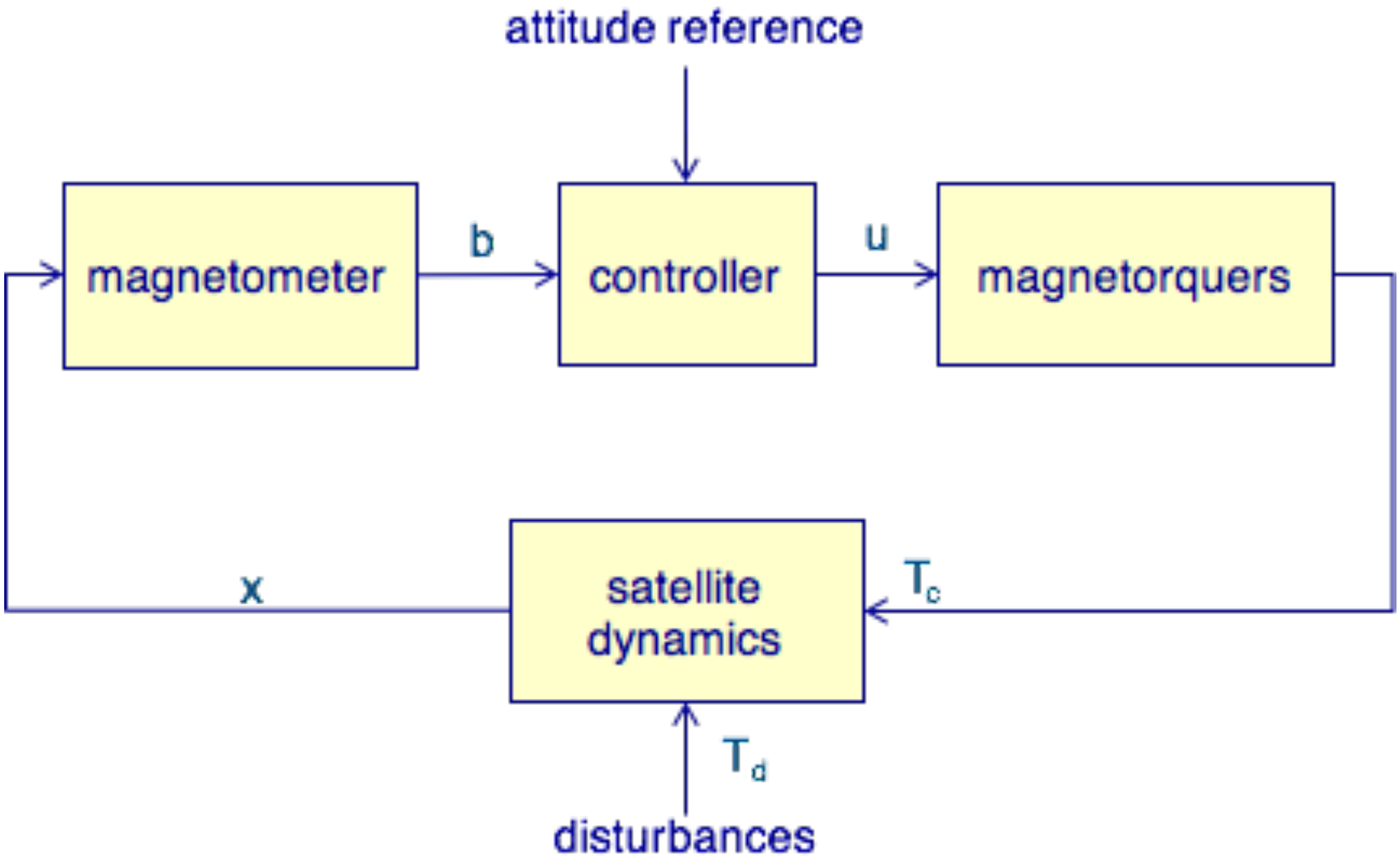


Attitude control frames

- Body reference frame XYZ
  - antenna on Z axis
- Orbital reference frame $X_0Y_0Z_0$
  - inertial for short intervals
- Attitude reference
  - align Z with Z_0
  - slow rotation around Z



Magnetic attitude control



Magnetometers / magnetorquers

- Magnetometers provide a measurement of the Earth's magnetic field components in the body frame
  - $\mathbf{b}$: magnetic field vector
- Magnetorquers generate a control torque normal to the orbit
  - $\mathbf{m}$: magnetic moment vector
    - ✓proportional to the current in each magnetorquer coil
      - $\mathrm{m_i} = AN \cdot I_i$

Validation steps: Model-in-the-loop

- Preliminary validation of control algorithm
- Use a model of the ACS, together with models of the space environment and the spacecraft dynamics, to assess the validity of the control law and the design parameters.
- Usually carried out by a control engineer using a simulation tool.
  - Simulink is commonly used for ACS development.

Validation steps: Processor-in-the-loop

- A further step to full validation is running the control software on actual hardware, while still using simulation models of the sensors, actuators, and spacecraft dynamics.
- A software validation facility (SVF) uses an auxiliary computer, linked to the OBC by a serial line, to run a simulation model of the Earth's magnetic field and the satellite dynamics.
  - In this way, engineering values (Nm and T) can be interchanged.
- The code of the control algorithm is generated with the Simulink Code Generator, and compiled and linked with the on-board software using the GNAT development environment.
- Functional & real-time behaviour can be validated.

Validation steps: Hardware-in-the-loop

- The next step is to include a model of the actual magnetometers and magnetorquers in the simulation model, and connect their inputs and outputs to the OBC hardware by means of its analog and digital input and output lines.
- This simple kind of HIL setup allows the operation of input/output devices, as well as signal conditioning hardware and software, to be validated.
- Full HIL validation, though, requires using the real magnetometers and magnetorquers hardware and, ultimately, the whole satellite structure, on a setup which enables the attitude of the spacecraft to evolve in a free fashion.

Technology Readiness Level (TRL)

The technical maturity of instruments and spacecraft sub-systems with respect to a specific space application are classified according to a "Technology Readiness Level" (TRL) on a scale of 1 to 9. ESA uses the ISO standard 16290 Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria assessment.

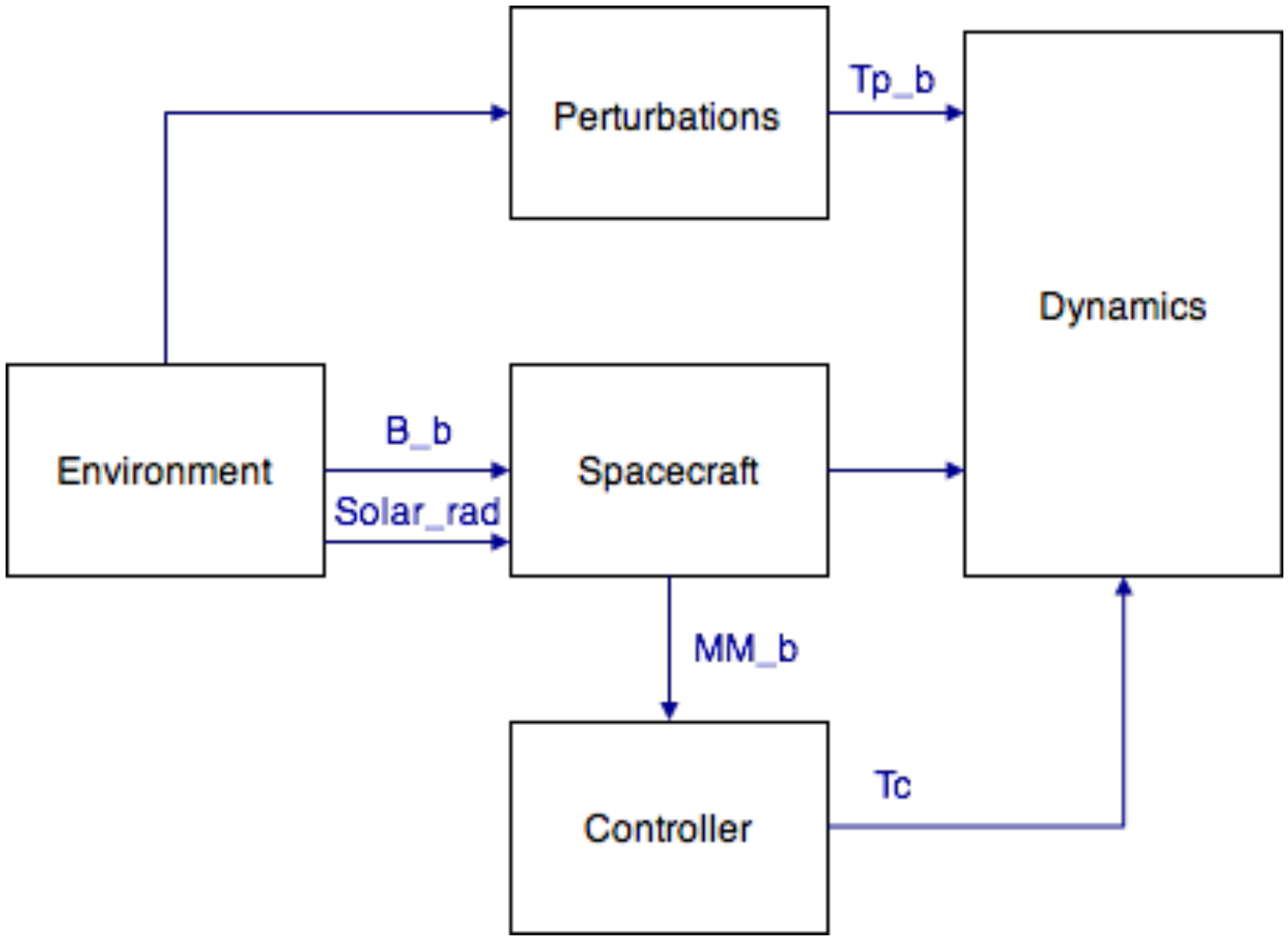
ISO Technology Readiness Level Summary

TRL Level Description

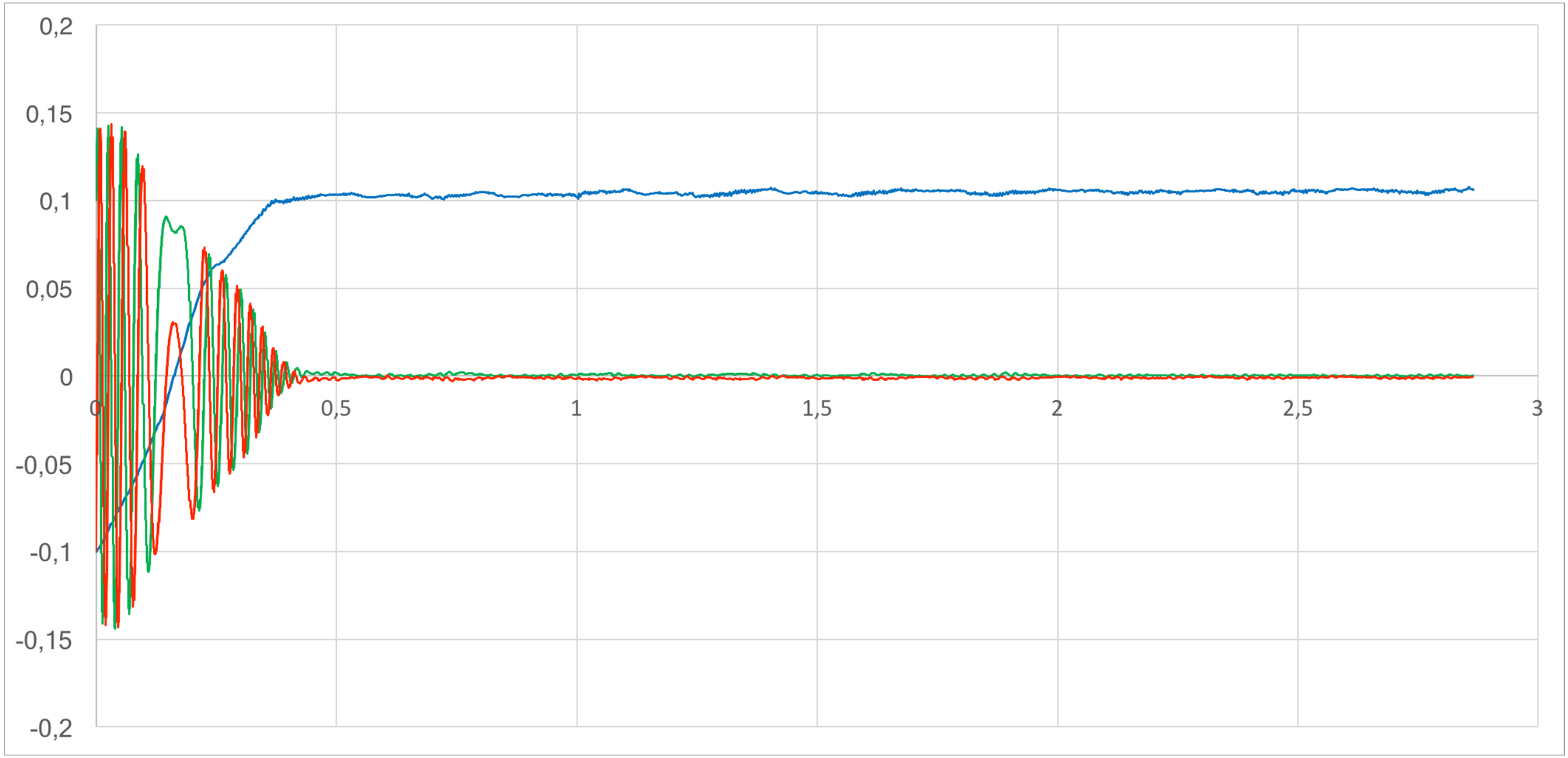
1 Basic principles observed and reported
2 Technology concept and/or application formulated
3 Analytical and experimental critical function and/or characteristic proof-of-concept
4 Component and/or breadboard functional verification in laboratory environment
5 Component and/or breadboard critical function verification in relevant environment
6 Model demonstrating the critical functions of the element in a relevant environment
7 Model demonstrating the element performance for the operational environment
8 Actual system completed and accepted for flight ("flight qualified")
9 Actual system "flight proven" through successful mission operations

http://sci.esa.int/sci-ft/50124-technology-readiness-level

ACS MIL (Model In the Loop) validation

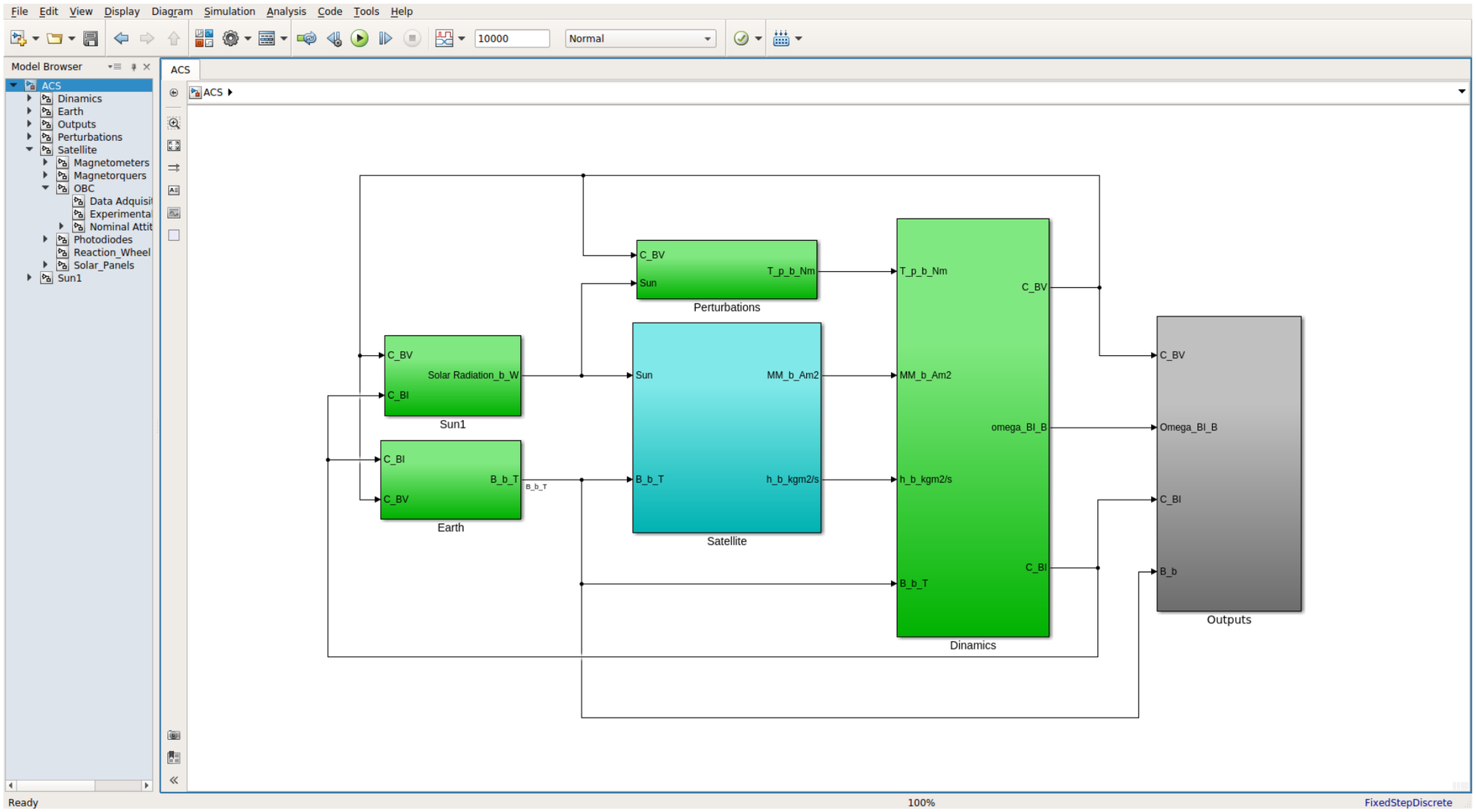


Angular velocity stabilization



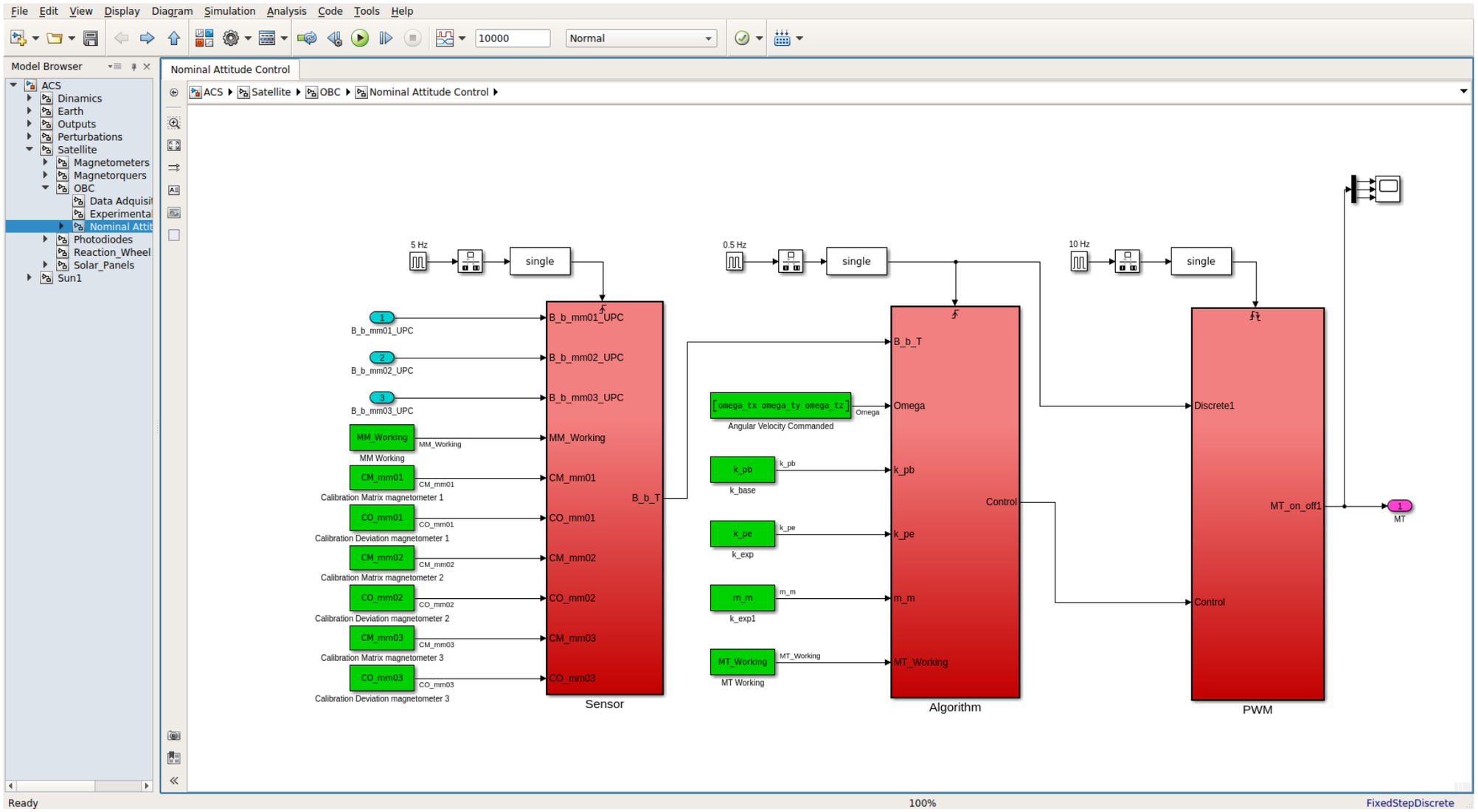
Simulink model

- Run matlab and open ACS.slx from directory LAB/ACS.



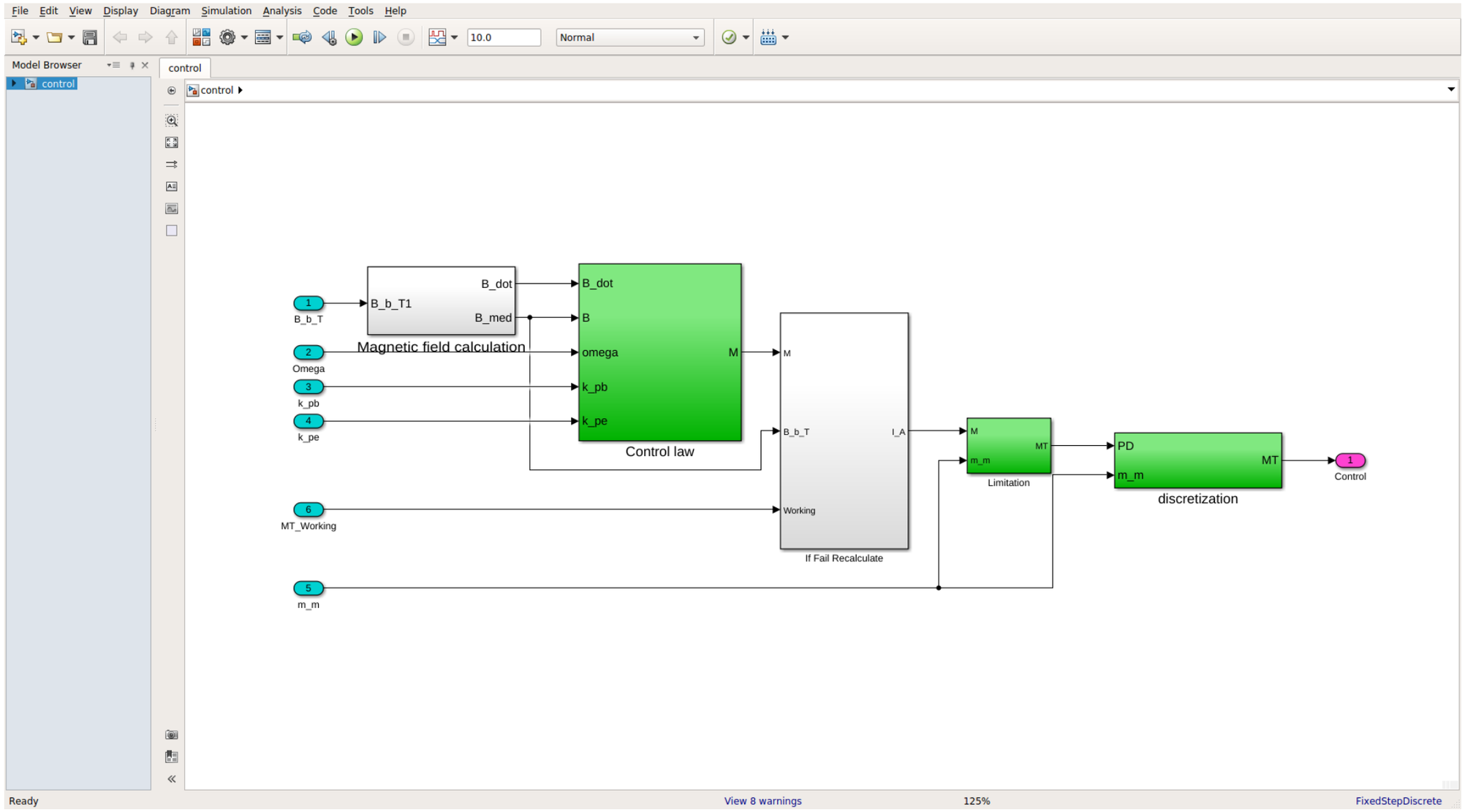
Simulink model

- Navigate to nominal attitude control.
- Simulate and verify angular velocity stabilization



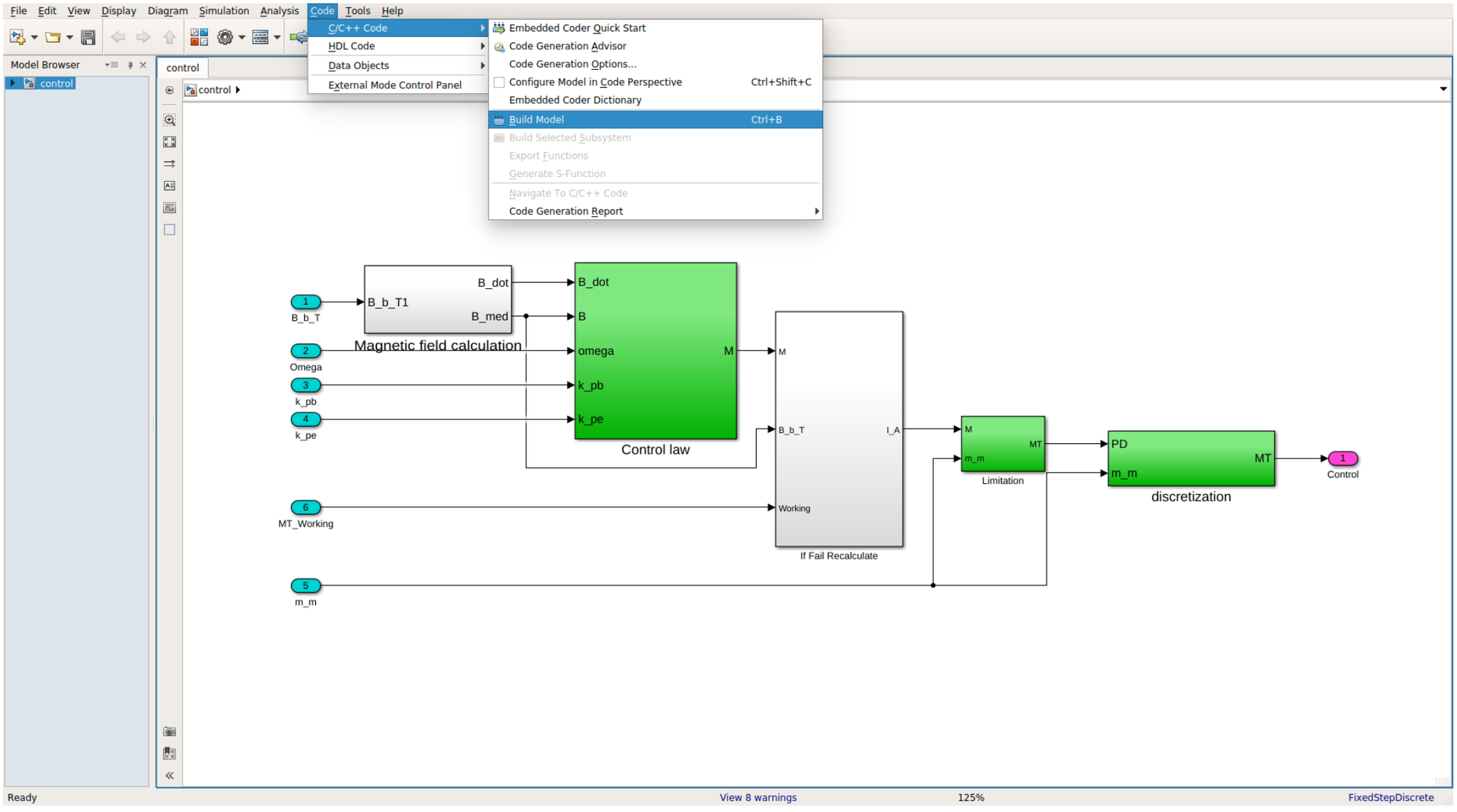
Simulink model for code generation

- Open control.slx from directory LAB/ACS_PIL



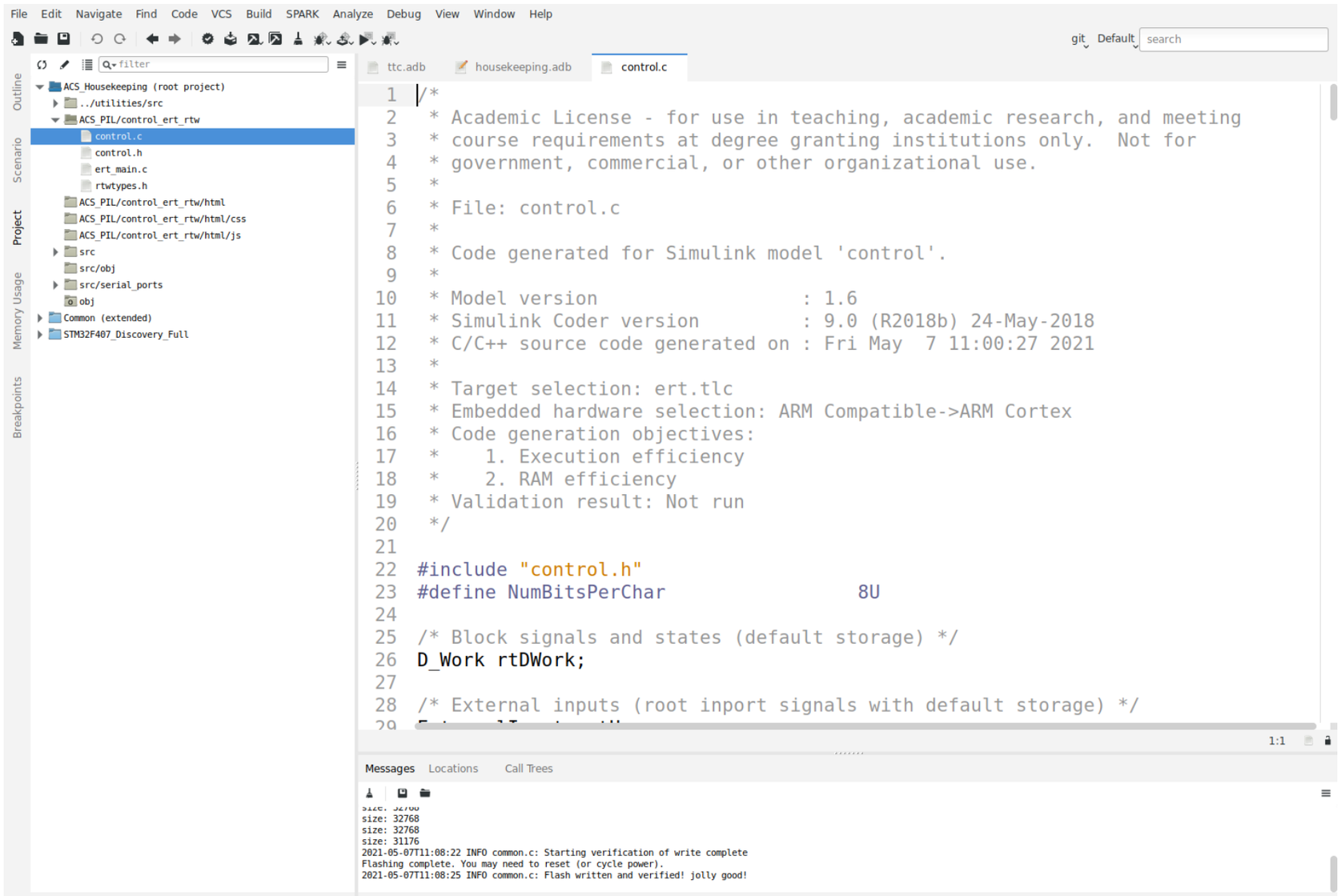
Code generation

- Generate code with Embedded Coder toolbox
- Take a look to code generation report



Code generation

- The generated C code is located at LAB7/ACS_PIL/control_ert_rtw
- Launch gnatstudio and open LAB7/ACS_housekeeping.gpr



ACS implementation

File Edit Navigate Find Code VCS Build SPARK Analyze Debug View Window Help

git Default search

ttc.adb housekeeping.adb control.c adcs.adb

```
24 package body ADCS is
25
26    -- controller block input and ouput objects must be global
27    Control_Input : Controller_Input;
28    pragma Export (C, Control_Input, "rtU");
29
30    Control_Output : Controller_Output;
31    pragma Export (C, Control_Output, "rtY");
32
33    --  Initialize the ADCS subsystem
34    procedure Initialize is
35       procedure Control_Initialize;
36       pragma Import (C, Control_Initialize, "control_initialize");
37    begin
38       Control_Initialize;
39    end Initialize;
40
41    -- ADCS task
42    task body ADCS_Task is
43       procedure Control;
44       pragma Import (C, Control, "control_step");
45       Next   : Ada.Real_Time.Time := Ada.Real_Time.Clock + Initial_Delay;
46    begin
47       loop
48          delay until Next;
49          Control_Input.B_b_T := ADCS.HW.Get;
50          Control;
51          ADCS.HW.Put (Control_Output.Control);
52          Next := Next + Period;
53          STM32.Board.Red_LED.Toggle;
54       end loop;
55    end ADCS_Task;
56
57 end ADCS;
```

1:1 ✓

ACS Hardware interface

File Edit Navigate Find Code VCS Build SPARK Analyze Debug View Window Help

git Default search

ttc.adb housekeeping.adb control.c adcs.adb adcs-hw.ads adcs-parameters.ads adcs-hw.adb

```
29 package body ADCS.HW is
30
31    package MF is new Message_Four_Bytes (Four_Bytes => Interfaces.IEEE_Float_32);
32
33    procedure Initialize is
34    begin
35       null;
36    end Initialize;
37
38    function Get return MGM_Readings is
39       Ingoing : aliased Message (Physical_Size => 4);
40       Data : MGM_Readings;
41    begin
42       for i in MGM_Readings'Range loop
43          Get_Fixed (COM, Ingoing'Unchecked_Access);
44          MF.Unset (Ingoing, Data (i));
45       end loop;
46       return Data;
47    end Get;
48
49    procedure Put (Output : ADCS_Vector) is
50       Outgoing : aliased Message (Physical_Size => 4);
51    begin
52       for i in ADCS_Vector'Range loop
53          -- N := (i-1)*4 +1;
54          MF.Set (Outgoing, Output (i));
55          Put (COM, Outgoing'Unchecked_Access);
56       end loop;
57    end Put;
58
59 begin
60    Initialize (COM);
61    Configure (COM, Baud_Rate => 115_200);
62 end ADCS.HW;
```

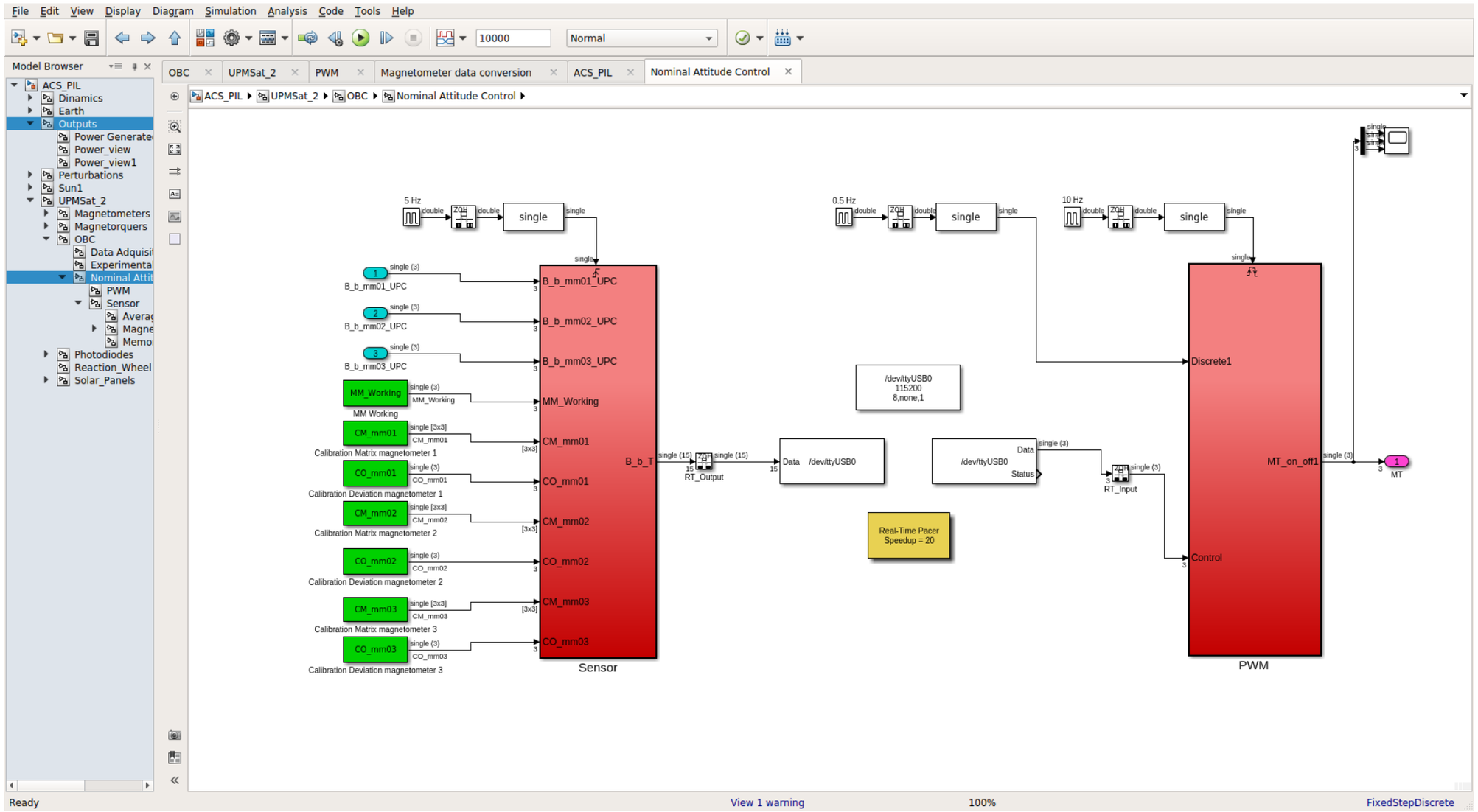
1:1 ✓

Study the code

- Connect the serial line to the host PC
  - as in LAB5 but do not run PutTTY
  - serial line will be used for interchanging sensor readings and actuations
- Build the executable and debug on the board
  - as in LAB4
- Nothing will happen because OBDH is waiting host PC inputs

Simulink model por PIL (Processor In the Loop) validation

- Open ACS_PIL.slx from LAB7/ACS_PIL directory
- Navigate to nominal attitude control.

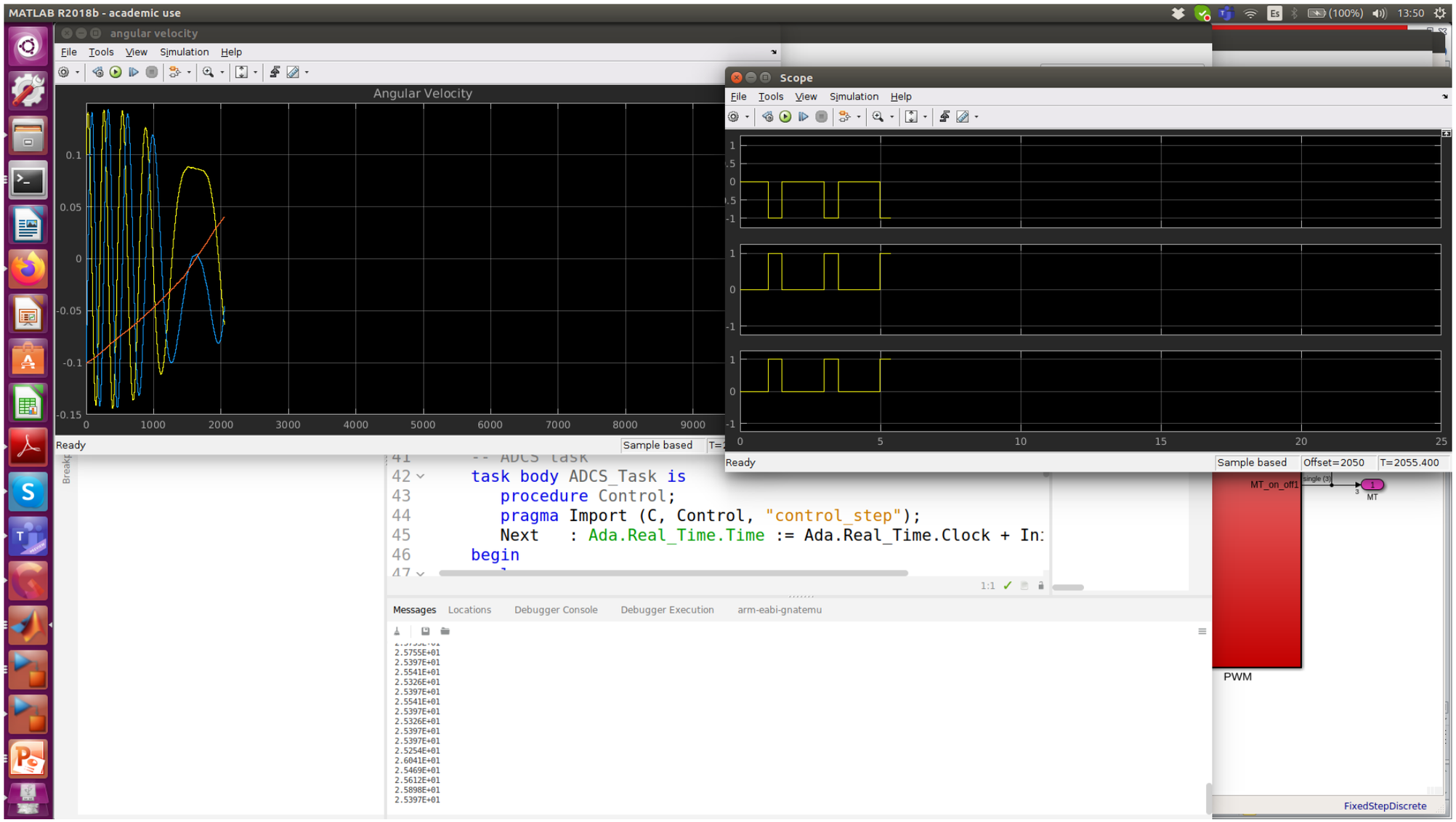


Study the model

- The control block has been replaced by a connection to the serial line
  - edit the serial configuration block and put the name of the serial line of your PC
  - additional rate transition blocks have been added to ensure a proper communication
- A Real-Time pacer has been added to the model to set the simulation speed
  - Speedup = 1 should be used but it is too slow
- Start the simulation and verify angular velocity stabilization
  - Now OBDH runs and LEDs are toggled

Simulink PIL validation

- Compare angular velocity stabilization with the original full-Simulink model.



Make changes and play

- Default parameters for control blocks can be changed in Ada source file ACS-parameters.ads
  - Default_omega is the consigned angular velocity
  - Default_MT_Working contains the operational magneto-torques
  - In UPMSat-2 the parameters can be changed by TC
- The initial angular velocity can be changed in Simulink source code initialization.m
  - omega_BI_B0 = [0.1;-0.1;-0.1];

Hardware In the Loop

- To reach a higher TRL, a more realistic operational environment is needed
  - In UPMSat-2, ADC hardware was also included in the loop
  - A SVF host with analog input/outputs had to be set up in order to generate magnetometer outputs and read magnetorquer actuations.
- Much more sophisticated operational environments are possible.
  - However, they have a high cost