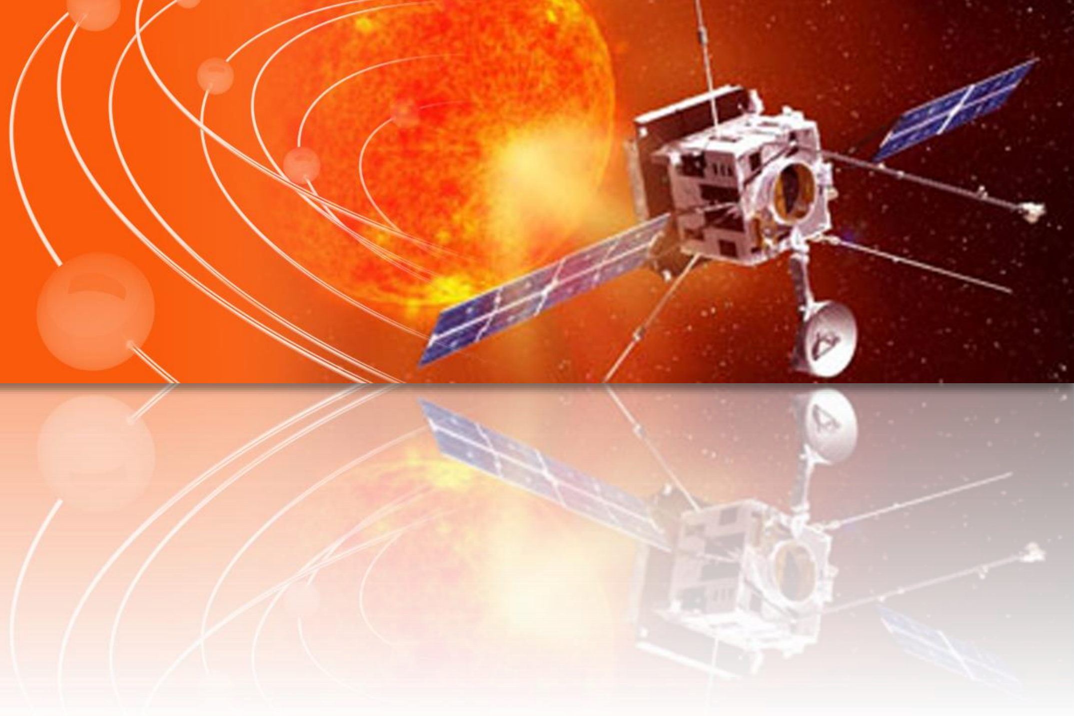

Design of the Attitude and Orbit Control System for ESA's Solar Orbiter

Colin Maule and Andrew Pollard
Tessella Ltd.

MATLAB Expo Benelux, 20 June 2017

Overview

- Introduction to Tessella
- Our part in the Solar Orbiter programme
- Control Engineering with MathWorks
- Integrating MathWorks into large projects

Altran

GLOBAL LEADER IN ENGINEERING
AND INFORMATION SERVICES

23 countries

29k
employees

300 of the
Global 500
are clients

1.9 bn euros
revenues

Industries:
from **automotive**
to **utilities**

Tessella

altran

Tessella, Altran's World Class Center for Analytics

We use data science to accelerate evidence-based decision making

OPERATIONS
UK, US, NL, FR, ES
DE, SE, PT

EXPERIENCE
30+ years of experience delivering 1000s of data analytics projects

DNA
Data is in our DNA. 250 of the brightest scientific minds, 50% hold PhDs

KNOWLEDGE
Unique combination of domain knowledge, data engineering expertise, maths & statistics excellence

Tessella

altran Part of the Altran Group

Our work allows businesses to improve profitability, reduce costs, streamline operations, avoid errors and out-innovate the competition.

Predicting the best coatings for ships. Reducing fuel costs by up to 15%

Data analytics powers H3 Biosciences drug research. Reducing time to go from lab to clinic by 75%

altran

Streamlining the creation of new oil wells . Saving BP $100s of million

Helping Unilever’s customers identify wholesome alternatives to existing preferences

Generating maps of disease risk in weeks not years. So medical intervention is better targeted

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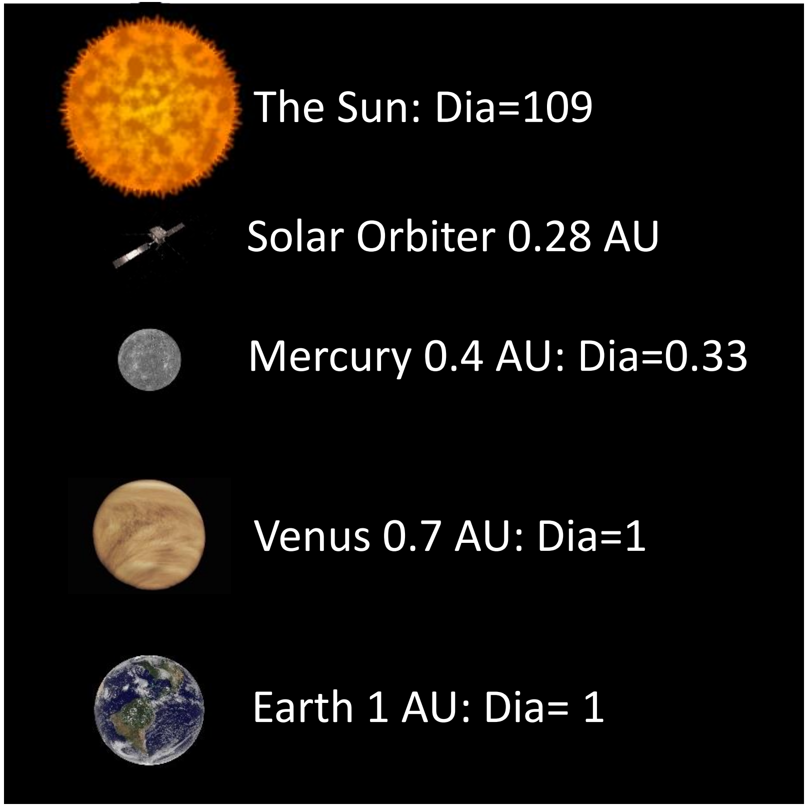
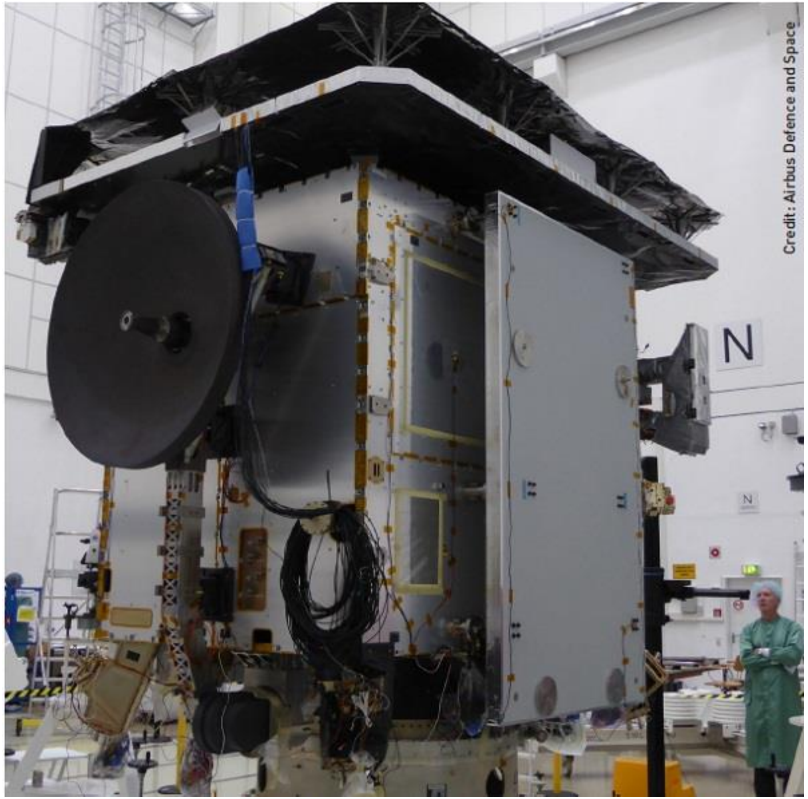
Tessella's part on Solar Orbiter

Fundamental AOCS requirements

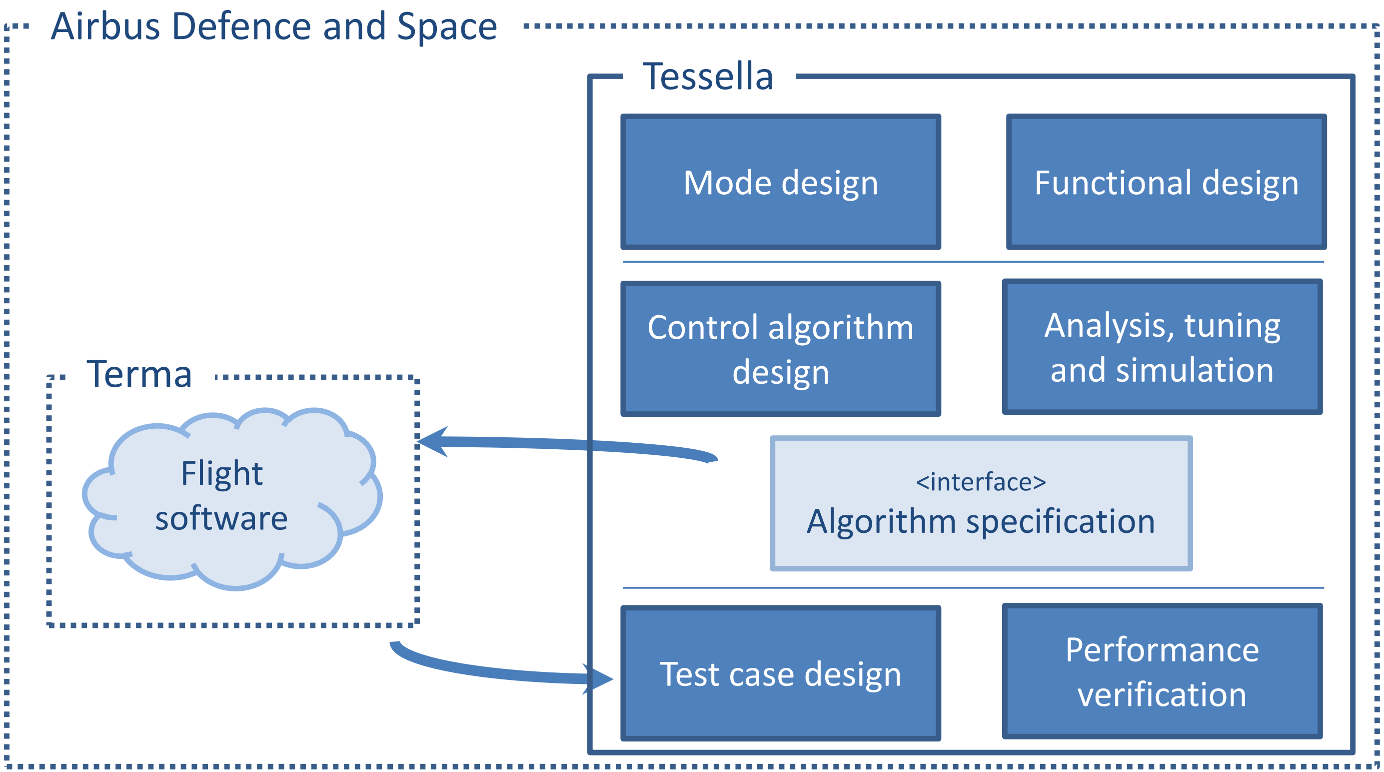
- Get it where it needs to be
- Point it in the right direction
- Keep it safe

Scale


The Sun: Dia=109
Solar Orbiter 0.28 AU
Mercury 0.4 AU: Dia=0.33
Venus 0.7 AU: Dia=1
Earth 1 AU: Dia= 1

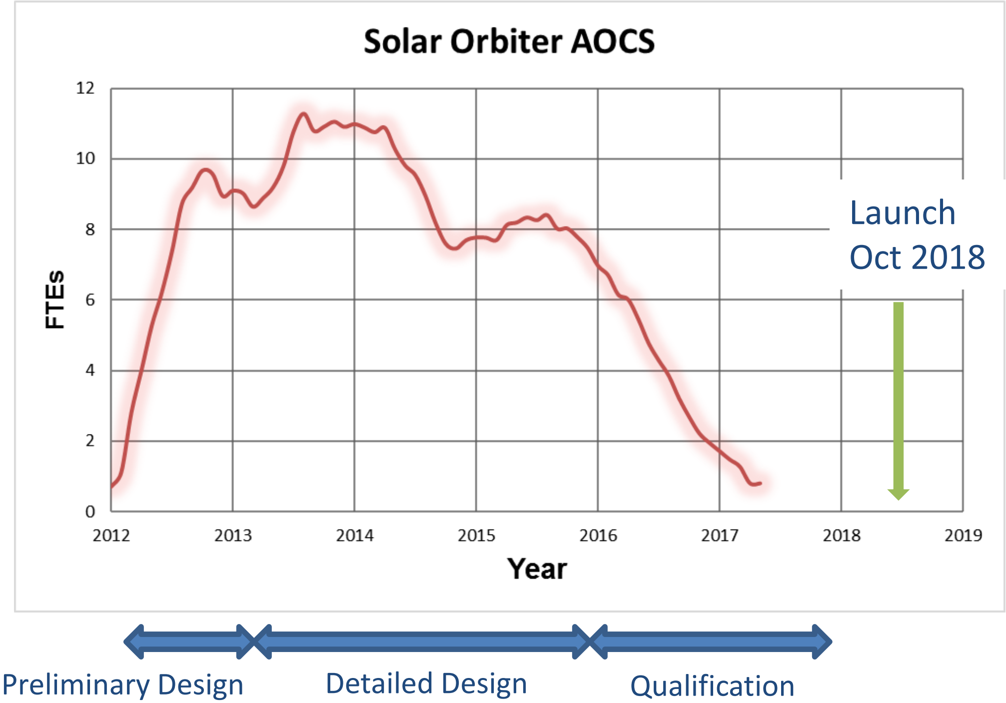

Credit: Airbus Defence and Space
N

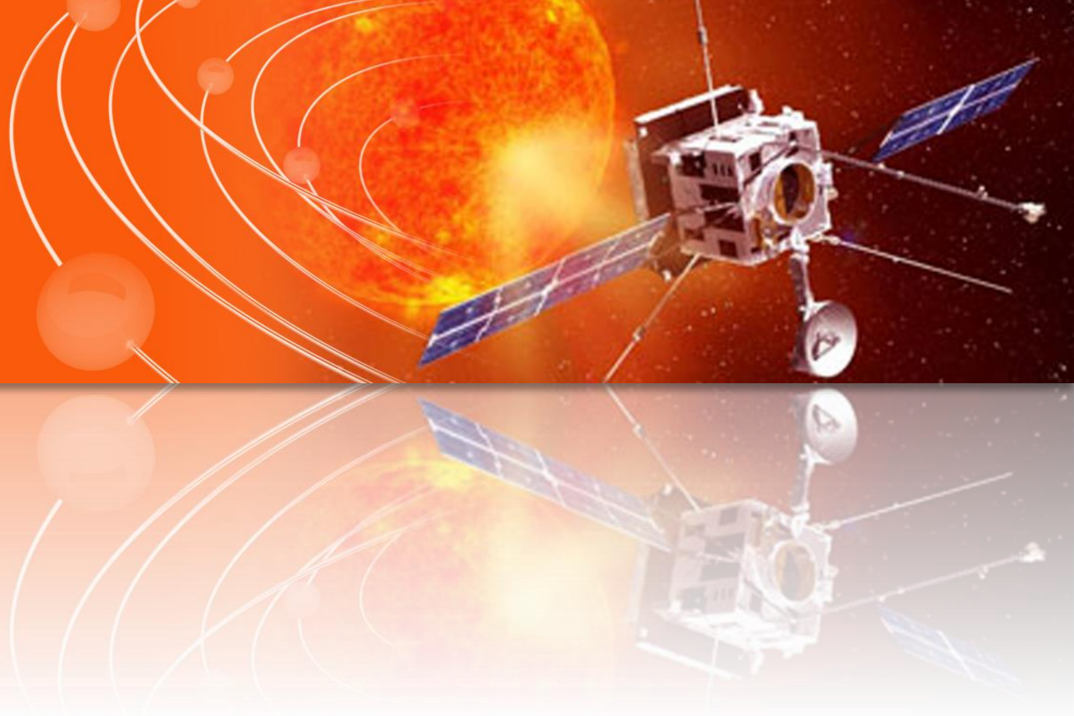
Scope



Airbus Defence and Space
Tessella
Mode design
Functional design
Control algorithm design
Analysis, tuning and simulation
<interface>
Algorithm specification
Terma
Flight software
Test case design
Performance verification

Tessella’s Part in the AOCS Subsystem



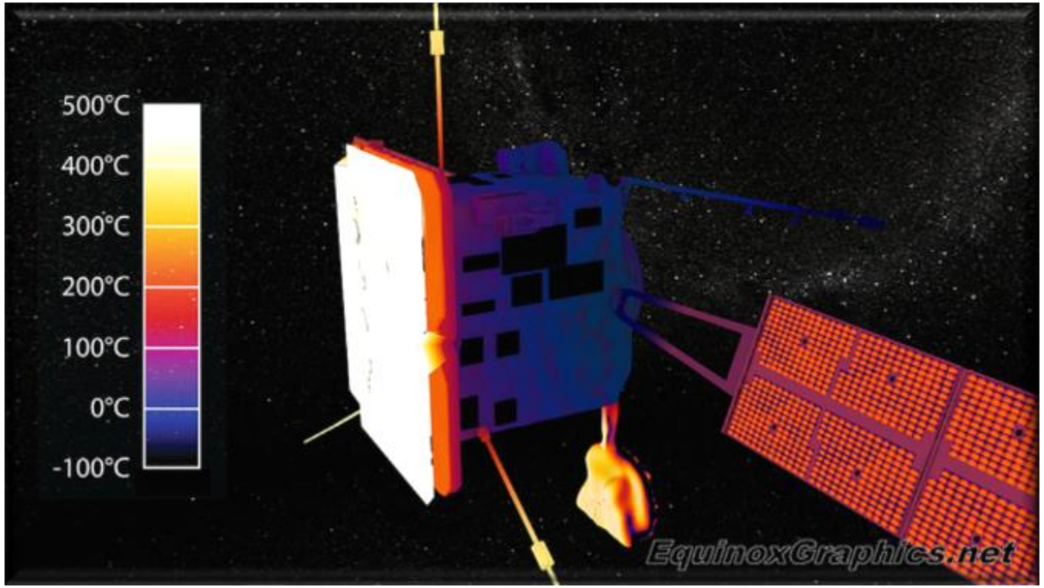


Control Engineering with Matlab & Simulink

Andrew Pollard
Mathematical Modeller & Algorithm Developer
Tessella Ltd.

Key Engineering Challenges

- Very extreme environment close to Sun
- Sun shield must remain pointed towards Sun, otherwise the heat will destroy the spacecraft
- Need to achieve precise trajectory for gravity assist manoeuvres

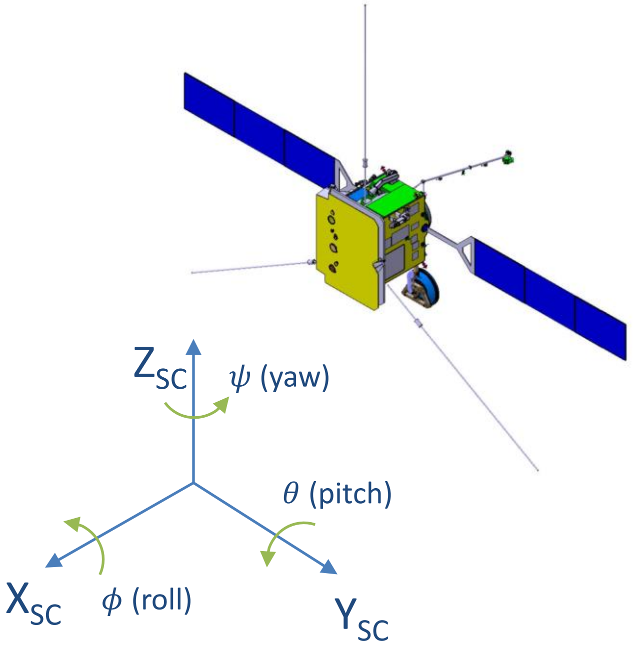


The Solution
AOCS: Attitude and Orbit Control Subsystem

- Autonomously control angle of rotation around 3 axes to keep spacecraft correctly oriented and execute ground-commanded manoeuvres

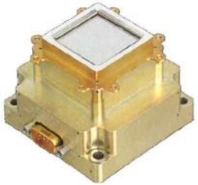
- Perform orbit correction manoeuvres with thrusters

- A critical subsystem!



Spacecraft AOCS Hardware

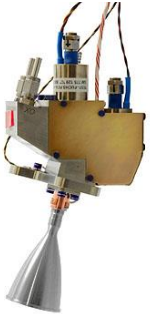
Sensors



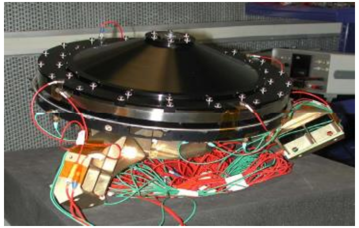
- Fine Sun Sensor

- Star Tracker
- Inertial Measurement Unit

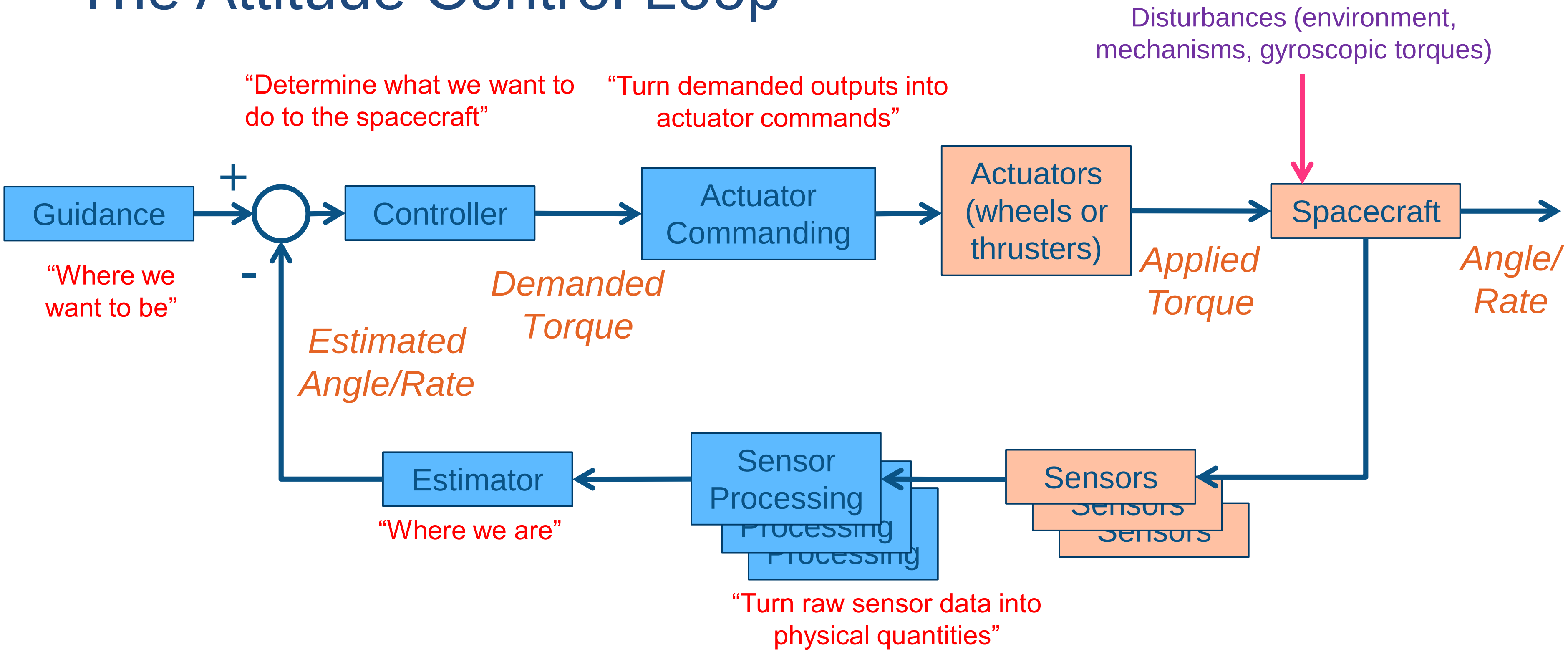
Actuators



- Reaction Control System (thrusters)
- Reaction Wheels



The Attitude Control Loop



Design Challenges	**Applicable MathWorks® tools:**
• Very stringent autonomous pointing requirements for making scientific observations: *Equivalent to pointing at this screen for 10 seconds… from Greenland!*	MATLAB & Control Systems Toolbox
• Flexible modes of appendages must not be excited	Control Systems Toolbox & Signal Processing Toolbox
• Very limited fuel	Optimization Toolbox
• Complex system to model	Simulink

Autonomy

- “Safe modes” of AOCS need to be fully autonomous to recover quickly from hardware failure

- Any ground intervention occurs slowly – can take ~ 10 minutes for signal to reach spacecraft

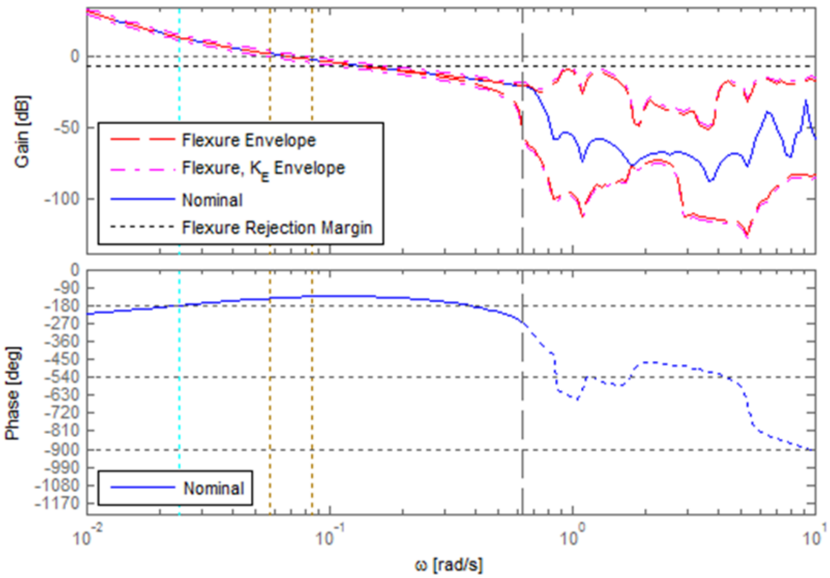
- Up to 70 days no comms at all during solar conjunction

- Required orbit corrections calculated by ground operations team, but manoeuvre is autonomous

Controller Design and Tuning

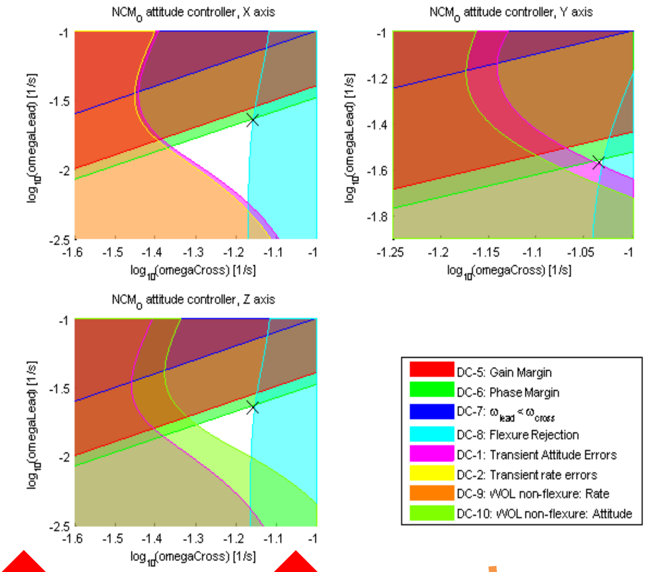
- Control Systems Toolbox used to compute envelope of frequency responses in presence of uncertainty and variability.
  - ➢ *Ensures spacecraft is stable with enough margin*
  - ➢ *Robustness*

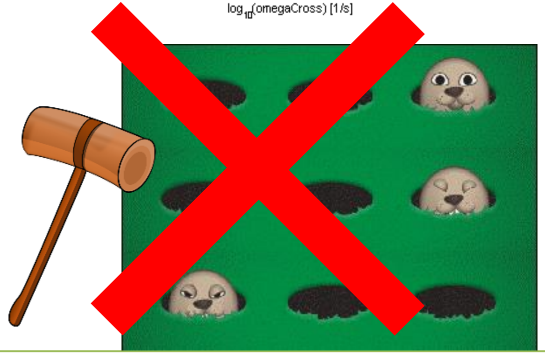
- Signal Processing Toolbox for candidate flexure filters. Genetic algorithm to investigate parameter improvements



Controller Design and Tuning

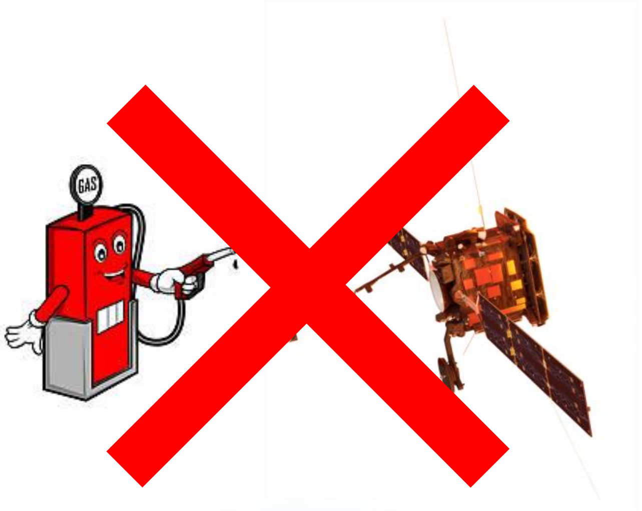
- In-house tools developed in MATLAB for repeated tasks, such as:
  - ➢ Constraint & sensitivity analysis
  - ➢ Automated controller tuning
  - ➢ Reporting of analysis results
- Allows rapid response to changes in inputs





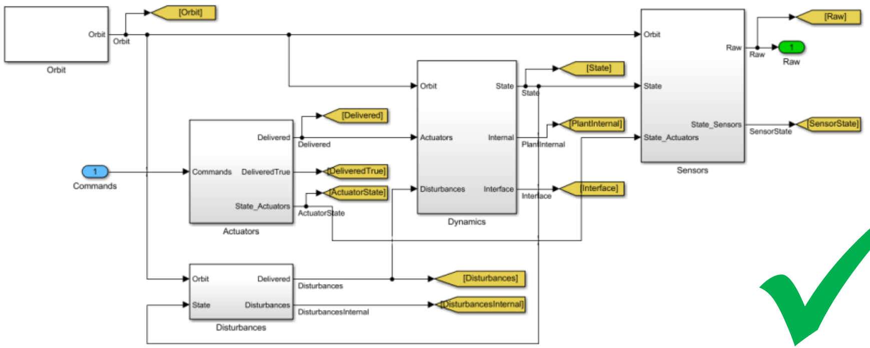
Controller Design and Tuning

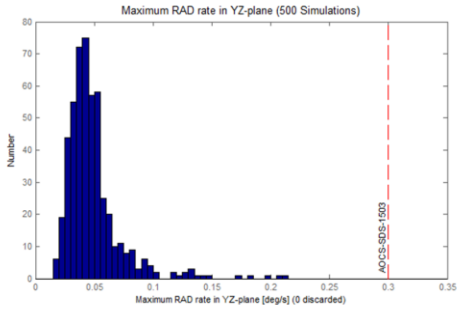
- Optimization toolbox for thruster modulation proving 6-D control
  - ➢ Given force and torque demands, determine which thrusters to fire and for how long
  - ➢ Minimise fuel consumption



Controller Design and Tuning

- Simulink for modelling full control loop, including hardware models
  - Rapid prototyping and design trade-offs
  - Verification of performance and robustness of control algorithms via Monte Carlo campaigns
  - Simulation of specific scenarios





Key Benefits of MathWorks-based Solutions

	Benefits
• Control Systems toolbox for controller design	The industry benchmark. Nothing else comes close for control engineering
• Optimization toolbox for thruster modulation	Attitude control will use only 40 kg propellant in 10 years
• Simulink for modelling & simulation of full system	No other tool gives us the multidomain simulation capability and block diagram environment in a way that is scalable to represent complex systems. That is why we use Simulink.

Integrating MathWorks into Large Projects

Tessella

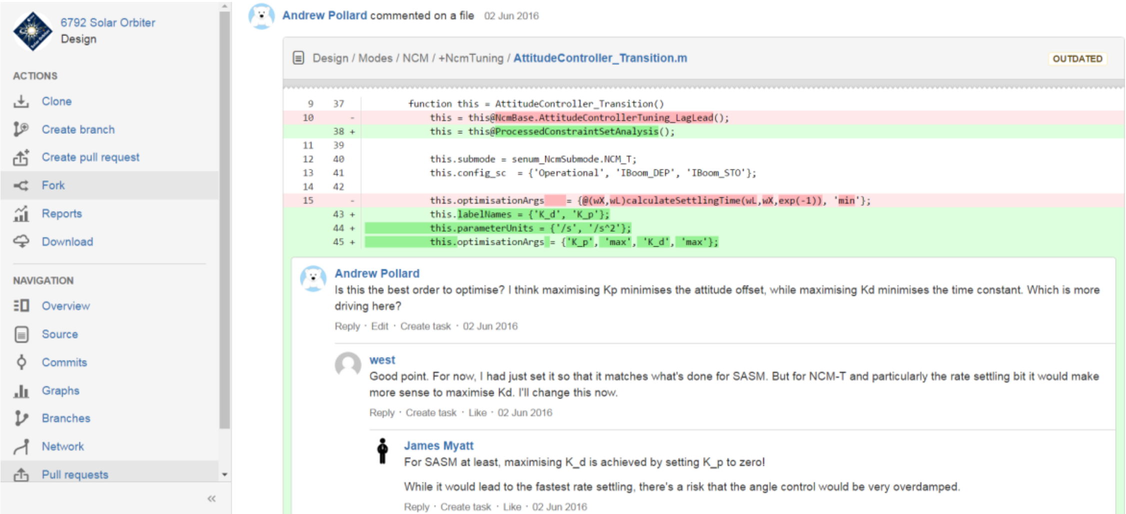
Part of the Altran Group

Further Challenges

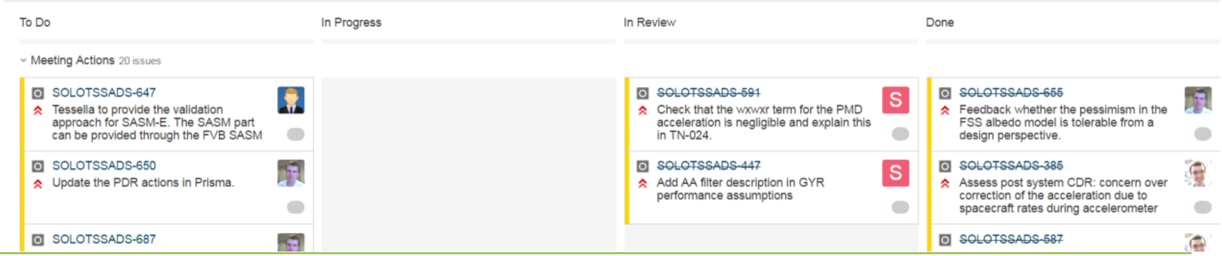
- Schedule
  - Changing the launch date is major!
- Knowledge transfer in a changing project team
- Large-scale system design problem
  - SW alone has 100s of tuneable parameters
  - Cannot be held in the head of 1 person!

Running the Project

- Very large collection of MATLAB code for long-term internal use by a large team
- Rigorous software engineering practices & tools appropriate for maintaining this code:
  - ➢ Bitbucket for distributed Git version control to promote code review, linked to CI server
  - ➢ JIRA Issue Tracking System linked to version control
  - ➢ TeamCity Continuous Integration for automated tests, and long-running analyses / simulations



MATLAB SIMULINK + Atlassian Bitbucket + JIRA + TeamCity

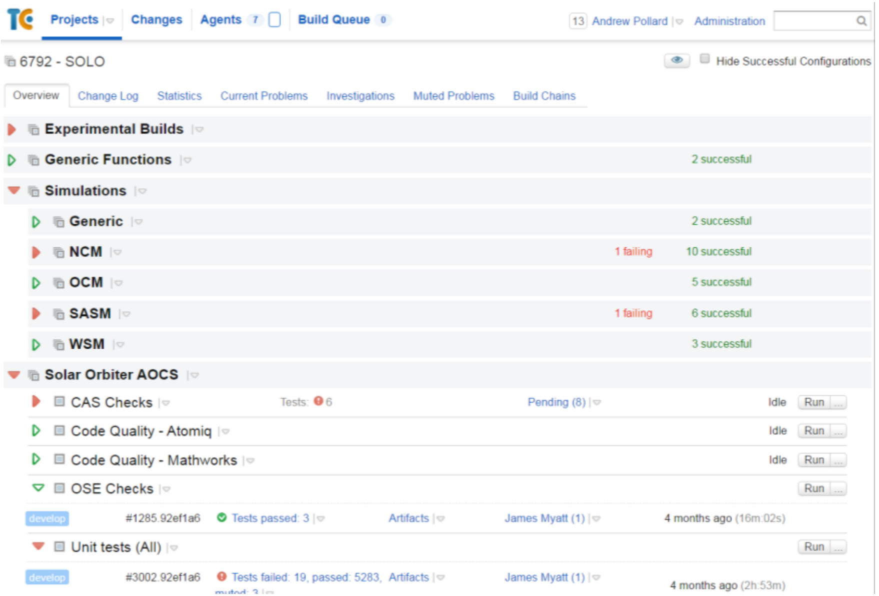


Benefits of Continuous Integration

We used continuous integration to:

- Automatically run unit tests & integration tests daily to check impact of code changes
- Help with configuration management of delivered files
- Run simulation campaigns on a server at the press of a button
- Run lengthy analyses and enable configuration management of the results

➢ Improved response time & verification



Object-Oriented Programming in MATLAB

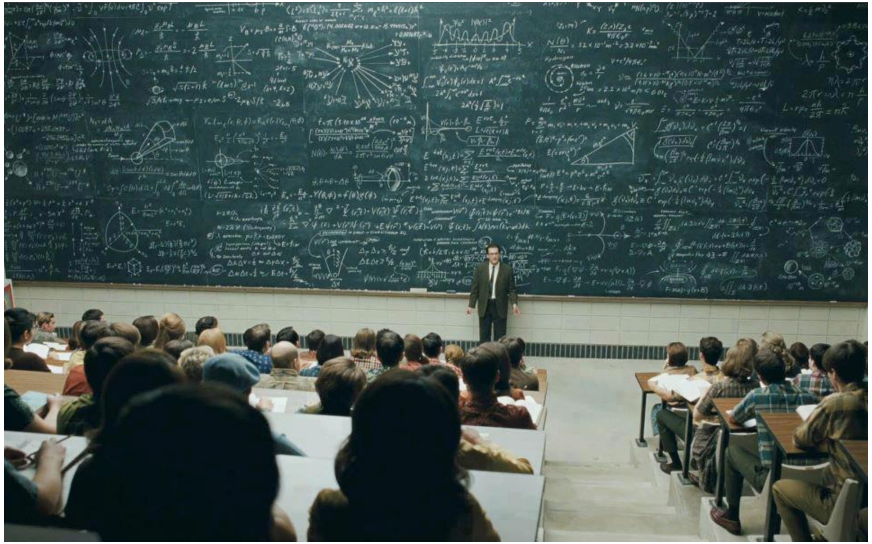
- Improve traceability of a parameter by storing metadata in an object, e.g.
  - where the value is documented
  - in which database version was it last changed
  - which program calculated it, etc.

- Automatic unit conversions reduce the occurrence of mistakes & hardcoded numbers

- Other uses of OOP included standardising how tuning & analysis functions are used
  - Easy to learn how to update documents

```
>> params.Design.SASM.Objective.LOS.sigma_ang_ctrl_farSun

ans =

  ParameterValue

           name: Design.SASM.Objective.LOS.sigma ang ctrl farSun
     design ref: calculateSASMPointingObjectiveLOS
      reference: SASM Tuning and Stability Analysis (SOL.S.ASTR.TN.00373 2 draft)
         source: Objectives / DesignDB_SASM v4_01.xml
        version: 4.1
         author: TESSELLA
         status: Derived
       datatype: double

    value [rad]:
    0.0116

    value [deg]:
    0.6655
```

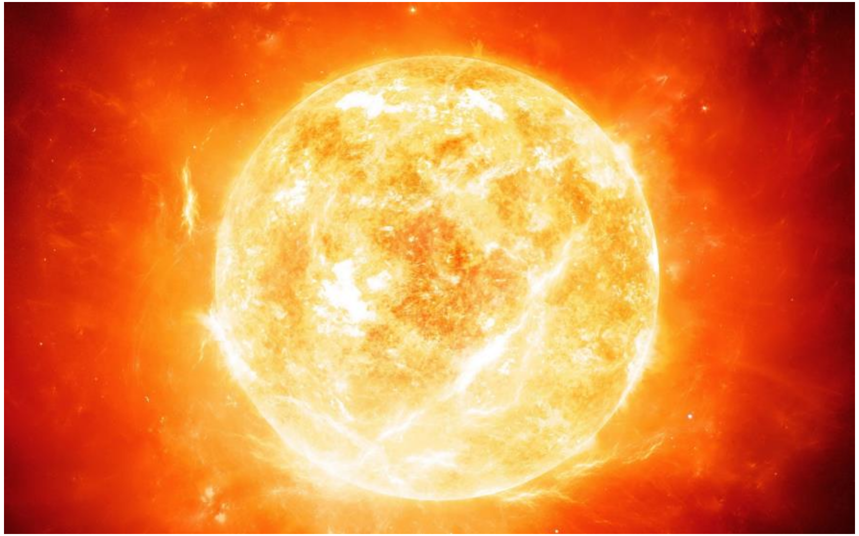
Lessons Learnt



- Results of complex analyses require high level of traceability
  - E.g. “Which parameters were used to produce these results from 2 years ago?”
  - Traceability requires configuration management
  - Continuous integration supports this
- Review of code, models & analysis has high value even if not deliverable
  - Everyone’s work is reviewed, and everyone reviews work
- Document your modelling assumptions
  - Turn into tests where possible

The Project Today

- Tessella's key deliveries are complete
- Detailed testing of AOCS algorithms being carried out by Airbus DS; we continue providing support
- Next stop… **THE SUN!**



Summary

- Solar Orbiter is an exciting ESA mission at the forefront of science, and a very complex engineering challenge
- Tessella made good use of MATLAB & Simulink to develop the algorithms for one of Solar Orbiter's key autonomous control systems
- Supporting tools and good software engineering practices were also used to get the best out of MATLAB on a large project, and these practices can be used in other domains

Further information

- MATLAB File Exchange
  www.mathworks.com/matlabcentral/fileexchange/
- Solar Orbiter
  sci.esa.int/solar-orbiter/
- Tessella
  Come and see our stand at the expo!
  https://tessella.com/
- MathWorks Training Services
  www.mathworks.com/services/training.html

Questions