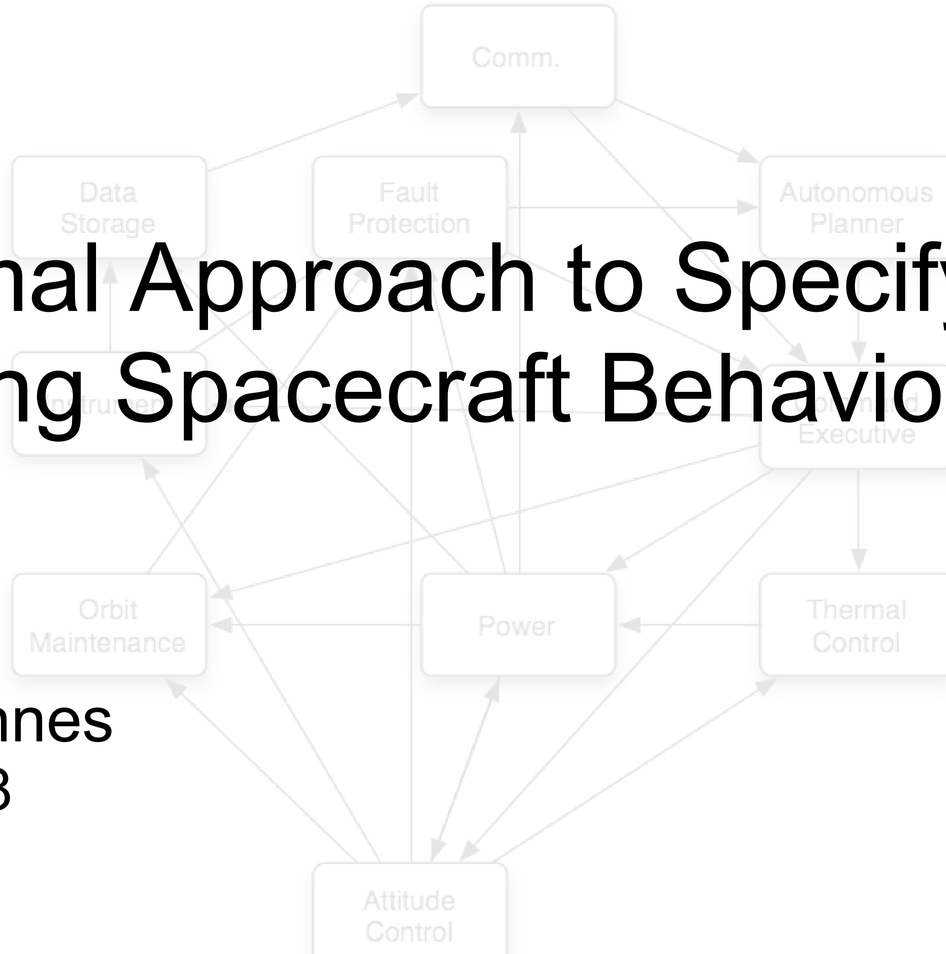
A Formal Approach to Specifying and Verifying Spacecraft Behavior



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Outline

- Motivation
- Existing work
- Approach
- Road ahead

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Spacecraft behavior: a loose definition

- Interaction with other systems
- Sequencing of inputs, outputs, and state changes
- System modes and mode changes
- System-level interaction between subsystems

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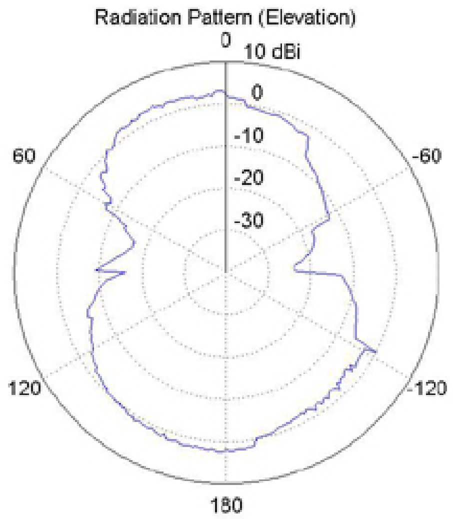
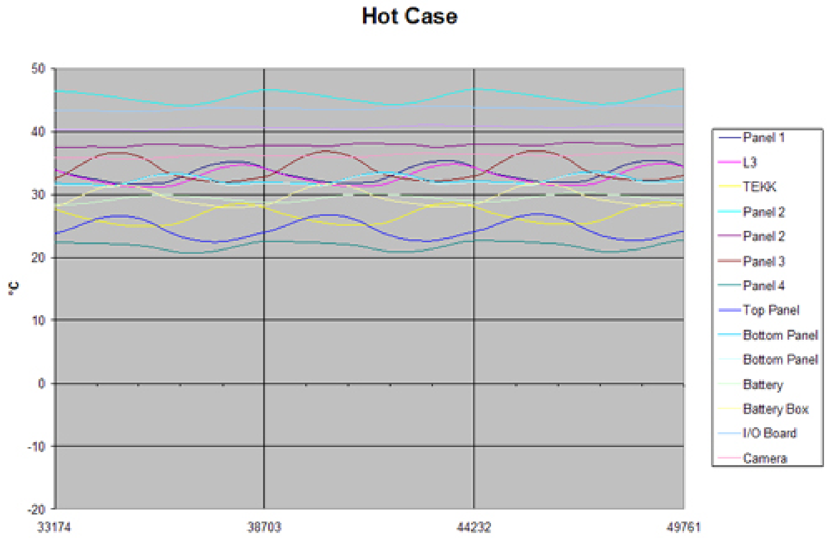
Current practice: subsystem design

- Subsystems are precisely specified through drawings, schematics, and code
- Subsystem designs undergo rigorous analysis





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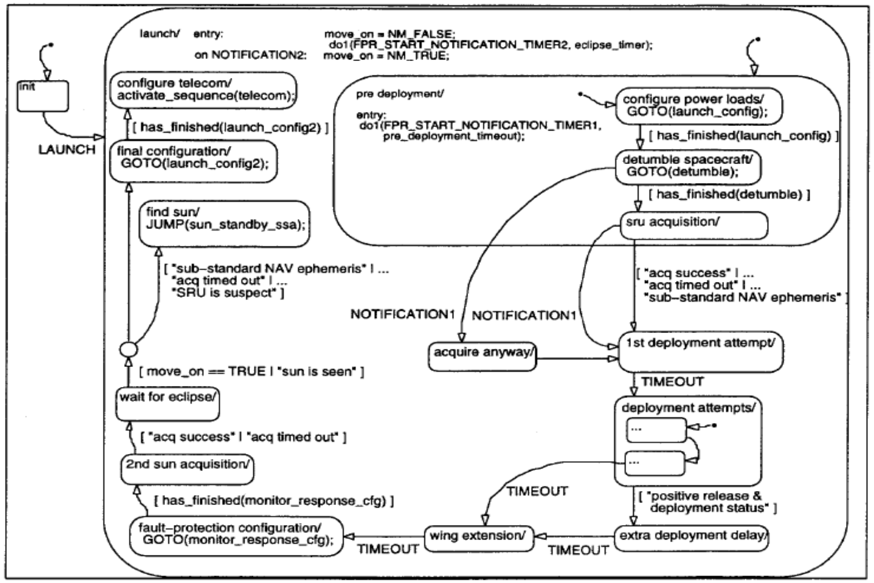
Current practice: spacecraft behavior

- Ambiguous behavior specifications

```
ACS.REQ.ASF.5 ACE SAFEHOLD MODE TRANSITIONS
Only a ground command or ACE box 8085 processor failure shall transition the ACS out of ACE
safehold.

ACS.REQ.SSF.2 SCS SAFEHOLD MODE TRANSITIONS
Only a ground command shall transition the ACS to a higher mode. The ACS shall transition back
to ACE safehold either by ground command, SCS microprocessor cold start, or by the ACS failure
detection and handling logic.
```

- Extremely limited design and analysis of behavior



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The problem

Without analysis, incorrect system behavior is unlikely to be detected until I&T

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Existing work

- NASA has experimented with formalizing behavior
  - Fault-protection verification with PVS [Easterbrook]
  - Promela/SPIN for a variety of verification tasks
    - Fault protection [Feather, Barltrop]
    - Autonomy [Havelund, Smith]
    - Software [Gluck, Visser]
  - Model-based programming with RMPL [Ingham]
- Limited formal modeling on non-NASA programs
  - SACI-1 C&DH fault-tolerance [Mota]
  - Abrixas embedded power controllers [Schlingloff]

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Approach

- Use *process algebra* to model spacecraft behavior
- Build simplified models that capture key behavior
- Link models to existing spacecraft terminology
- Create tools to make model-building easier

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Communicating Sequential Processes

- A *Process Algebra*

> Process = Abstract behavior
>
> Algebra = Operators and axioms

- A language for specifying concurrent behavior
- A language for modelling concurrent systems
- A theory for reasoning about behavior and systems

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Is it practical?

- CSP in industry: a few examples
  - INMOS – processor and logic design
  - Qinetiq – fault-tolerant ad hoc wireless networks
  - Praxis High-Integrity Systems – secure e-commerce
  - Daimler Aerospace – fault-tolerant software for ISS

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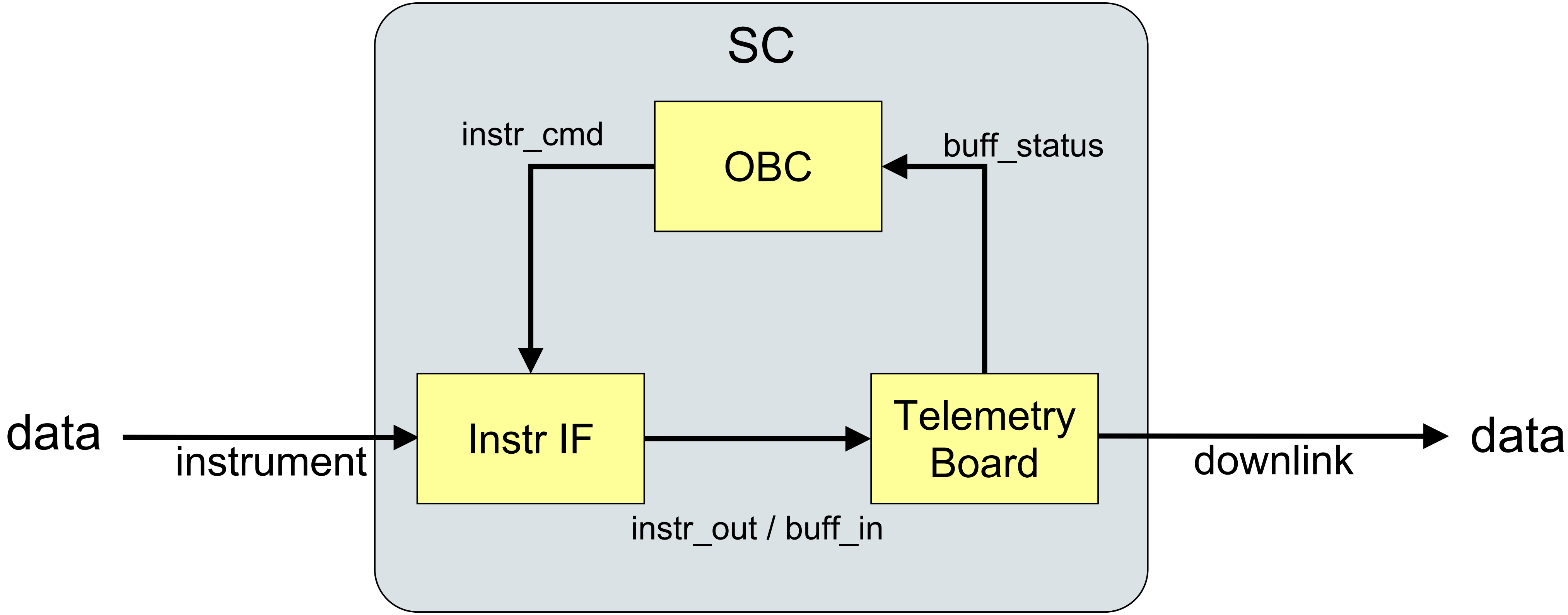
Simple example



$$
\begin{aligned}
SC \quad = \quad & (InstrIF \\
& [instr\_out \leftrightarrow buff\_in] \\
& TlmBoard) \\
& [instr\_cmd \leftrightarrow instr\_cmd, buff\_status \leftrightarrow buff\_status] \\
& OBC
\end{aligned}
$$

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Example process

Telemetry Board Behavior

- Both stores and transmits data
- Only accepts data if it has room
- Only downlinks if it has data
- Downlinks 1 data item at a time
- Signals changes in status

$$TlmBoard = buff\_status!notfull \rightarrow TB(MaxBuff, \langle\rangle)$$

$$\begin{aligned} TB(N, buff) \;=\;& (\#\,buff < N)\ \&\ Store(N, buff) \\ & \Box \\ & (\#\,buff > 0)\ \&\ Transmit(N, buff) \end{aligned}$$

$$\begin{aligned} & Store(N, buff) = buff\_in?d \rightarrow \\ & \quad \text{if } \#\,buff == N - 1 \\ & \quad \text{then } buff\_status!full \rightarrow TB(N, buff \frown \langle d \rangle) \\ & \quad \text{else } buff\_status!notfull \rightarrow TB(N, buff \frown \langle d \rangle) \end{aligned}$$

$$\begin{aligned} & Transmit(N, buff) = downlink!head\,(buff) \rightarrow \\ & \quad \text{if } \#\,buff == N \\ & \quad \text{then } buff\_status!notfull \rightarrow TB(N, tail\,(buff)) \\ & \quad \text{else } TB(N, tail(buff)) \end{aligned}$$

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Spacecraft behavior: definition revisited

- Function sequences
- Event sequences
- State transitions
- Mode transitions
- Behavior constraints
- Inter-subsystem communication
- Shared states and resources
- Triggering events

→ **CSP**

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Framework for behavior specification

- Combine behavior “components” to specify
  - Simple subsystem and systems behaviors
  - More complex autonomous behaviors
  - Fault responses

- Use COTS tools to verify that
  - Specifications are internally consistent
  - Specified behavior is correct

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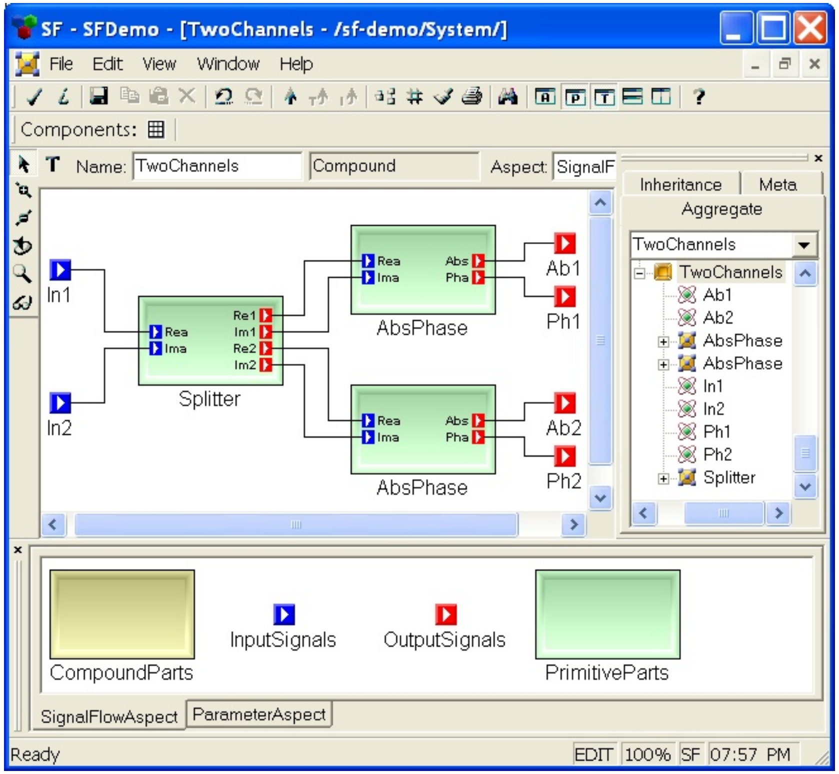
The road ahead

- Collaboration with Dr. Brandon Eames, Jared Crace, and Joe Graham
  - **Short term:** GUI specification tools (built on GME)
  - **Long-term:** code and FPGA generation from specs



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Summary

- Spacecraft system-level design should be as **rigorous** as subsystem-level design
- Our research
  - builds on **industrially-proven** formal methods
  - allows rigorous **system-level specification**
  - aims to make system-level rigor **accessible**

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