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Alternative Operations Concepts

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Evolution of Knowledge-based Applications for Launch Support

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Synopsis

- **Spacelift Telemetry Acquisition and Reporting System (The Aerospace Corporation developed and operated)**
  - Mission, History, and Environment
  - Forces shaping on-going evolution
- **Knowledge-based launch assessment**
  - Acknowledgements, Concept, and Process
  - Data, info, and knowledge: Sources and representations
- **Knowledge-based augmentation of architecture views**
  - Component, Layered, and Human interfaces
- **Knowledge-based launch support applications**
  - Heritage, Emerging, and Conjectured
- **Conclusions and Challenges**

☞ Experience suggests that unobtrusive knowledge-based applications can meet emerging launch support challenges ☜

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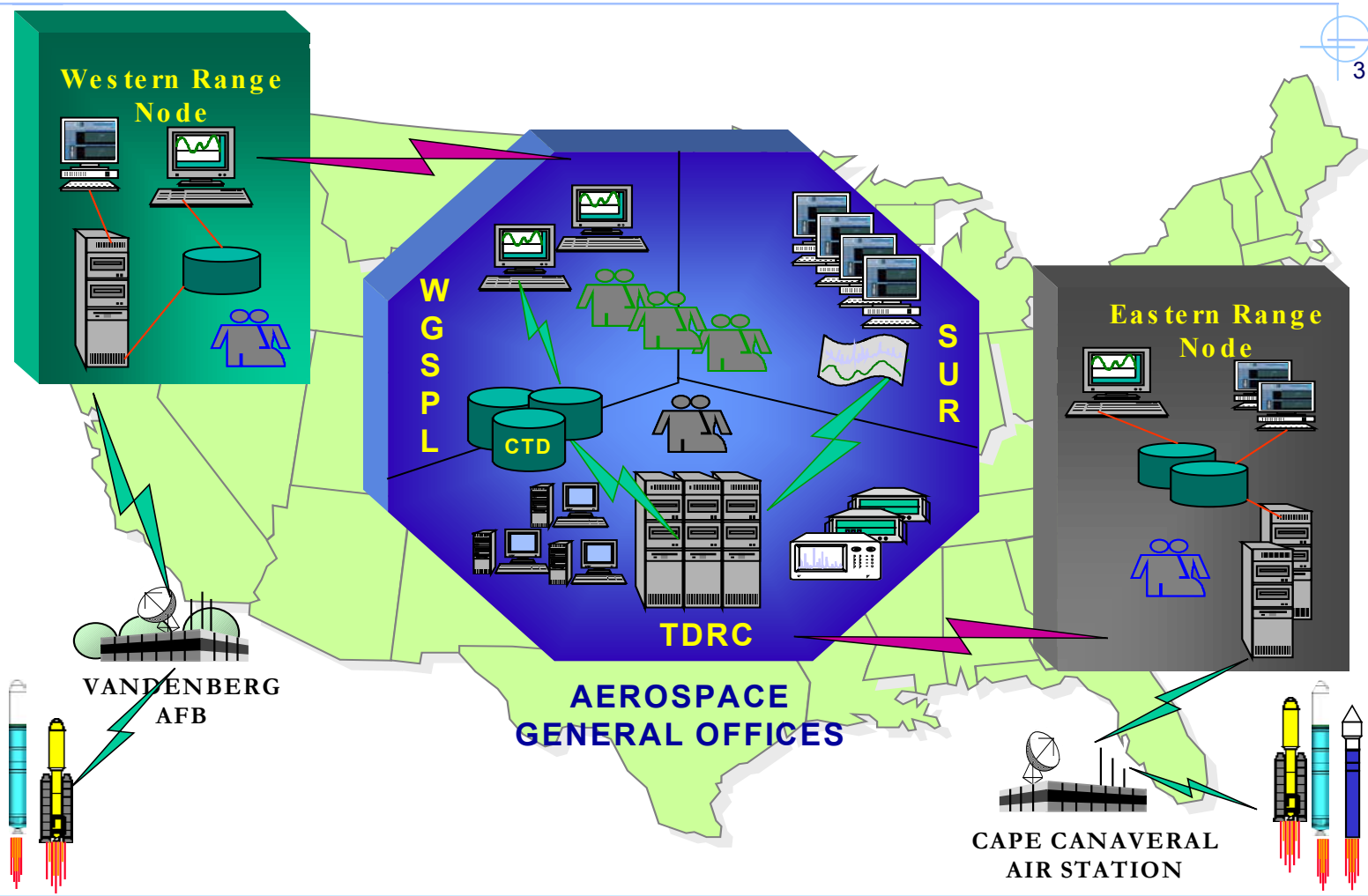
STARS Mission



Provide independent real-time and post-flight telemetry processing and analysis for a broad-spectrum of vehicles and operations

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STARS Evolution

Jan 1993

Launch Base Telemetry Processing High Performance Work Team initiated

STARS ASR funded (LPEAS)

Nov 1993

Initial GUI designed for TIVA vehicle

Concept of Operations Demonstration b/w VAFB and AGO; VAFB xmits down-sampled TIVA flight data via 56k modem

May 1994

VAFB System 550 installed

Dec 1994

AGO STARS supports first real time Cape launch K14

Full STARS equipment installed and activated in AGO and WRD

May 1995

First CTD datagather during real time launch support – K23/TC17

Nov 1995

Real time data interface to WRD STARS completed

First WRD STARS real time support – K15

New AGO DRC and SUR facilities completed

May 1998

First Atlas

First Titan II

First Delta

First Titan IVB

Dec 1999

CTD segmented gather capability

June 2000

STARS Network upgrade

SUR Common Software baseline established

Nov 2000

WRD STARS facility expansion completed

Dec 2001

ERD STARS Facility Activated

2002

Pathfinder EELV launch support

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Real-time Launch Assessment Environment

Courtesy The Aerospace Corporation

Experts immersed in mission-control-like atmosphere

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Forces Shaping On-going Evolution

- **Reduced availability of expert domain specialists, due to:**
  - Increased launch frequency
  - New launch vehicles (different sub-systems and configurations)
  - Personnel turn-over (reduced effectiveness, lost knowledge)
- **Increased data load per launch, due to:**
  - New launch vehicles (more and faster sensors)
  - Greater network and workstation hardware speed
- **Evolving requirements, including:**
  - Reduce cost, time, errors; increase capability, performance, quality
  - Paradigm shift in customer / contractor relationship from “oversight” to “insight”; unattended 24/7 operations
- **Evolving software technologies, including:**
  - COTS vendors moving from proprietary to open interfaces (i.e., Talarian SmartSockets to JMS)
  - Object- and component-oriented tools (i.e., UML patterns, Java Swing GUI, and EJB distribution)

☞ Many factors driving trend toward increased automation ☜

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A Challenge Problem: Turbopump Spindown

Determine the time it takes from the issued shutdown command for the turbo-pump to spin down to zero speed. Determine if any rubs occurred, as evident by a dramatic slope increase (both engines, both burns).

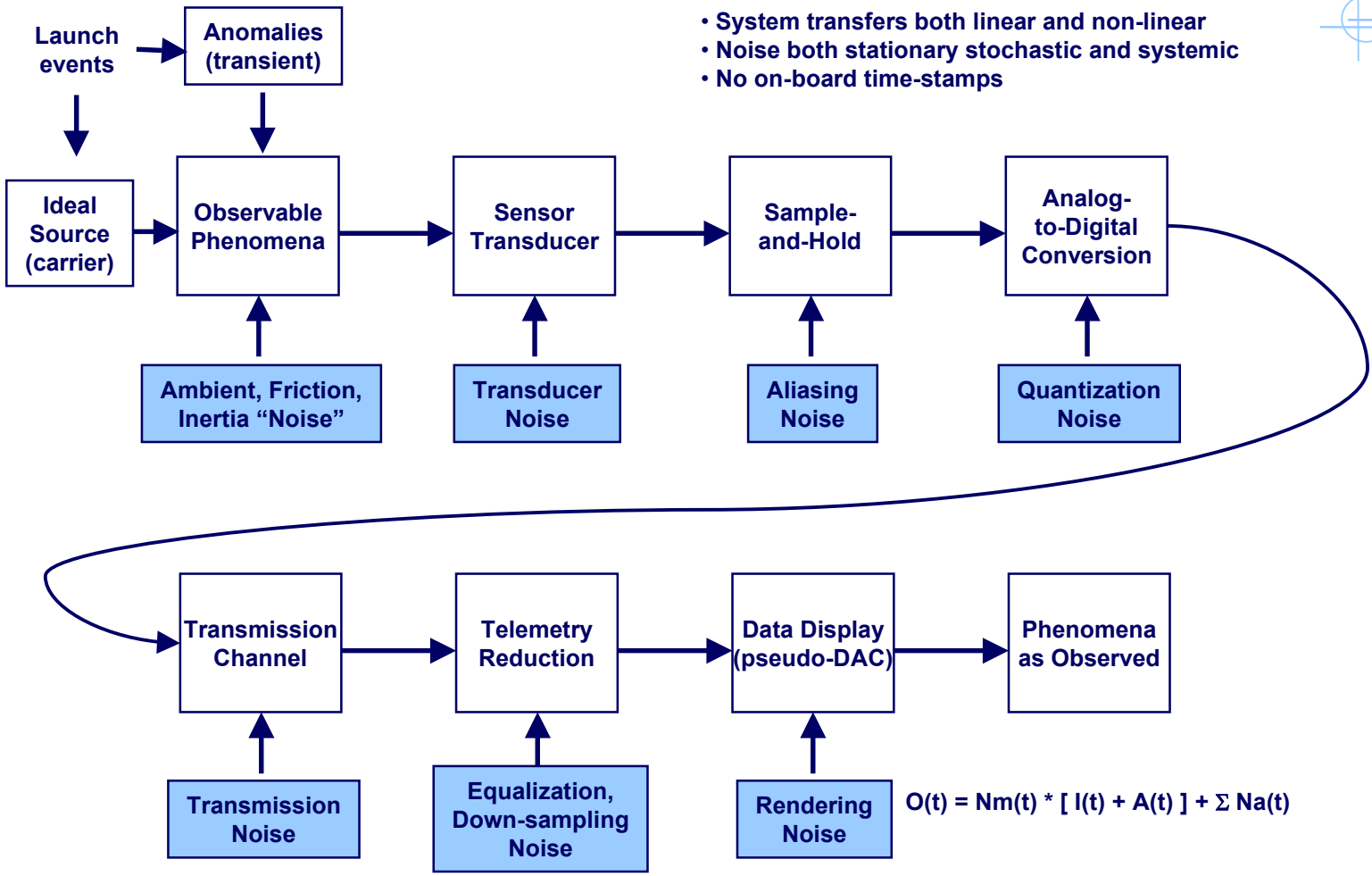
(Anomaly masked by noise , including under-quantization, under-sampling, and "random" shots).

(Multiple, overlaid launch pump speed plots)

Typical "new requirements" with numeric and logical aspects

Sources of Uncertainty

- System transfers both linear and non-linear
- Noise both stationary stochastic and systemic
- No on-board time-stamps



$$O(t) = Nm(t) * [\, I(t) + A(t) \,] + \Sigma\, Na(t)$$

☞ Values precise, but inaccurate;
Noise(s) masks carrier and anomalies in observed signal ☜

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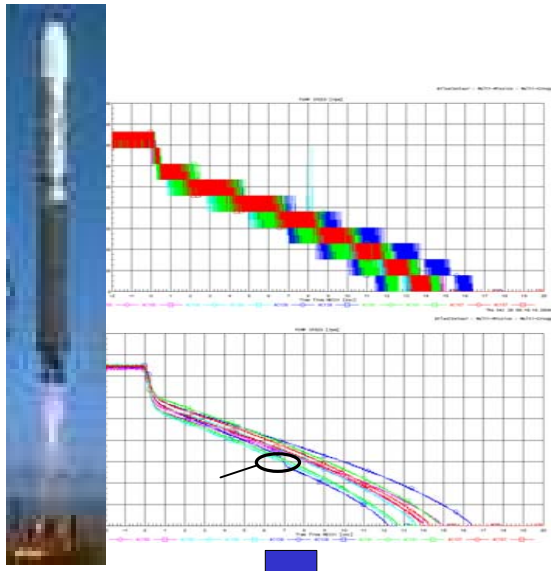
Knowledge-engineering Acknowledgements

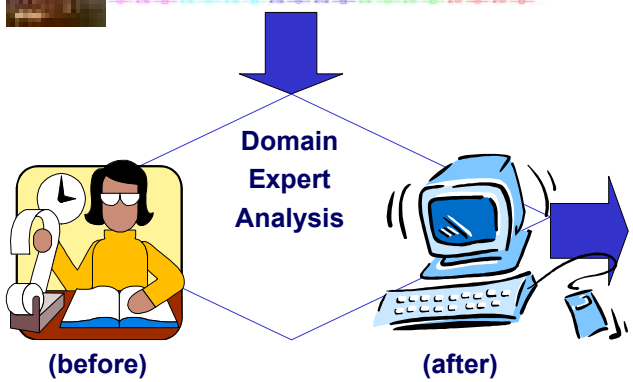
- **Program support for knowledge-based applications engineering:**
  - Margaret Sazani, Bruce Mau, Pinfun Tsai, Joe Tomei, Ron Croyts
- **Engineering support for knowledge-based applications engineering:**
  - Ken Behring, Rich Gerardi, Manny Ruiz, Len Beck
- **Technical support for knowledge-based applications engineering:**
  - Paul Yuhas, Walt Green, Scott Zechiel, Brenda Kim, Don Sather, Regina Lozano, Susan Painter, Melodie Evans, Scott Turner, Charles Simmons

A few of the many who contributed to the success of STARS

Knowledge-based Assessment - Concept



Enhance user efficiency by automating tedious monitoring and analysis tasks and by focusing attention on exceptional conditions.

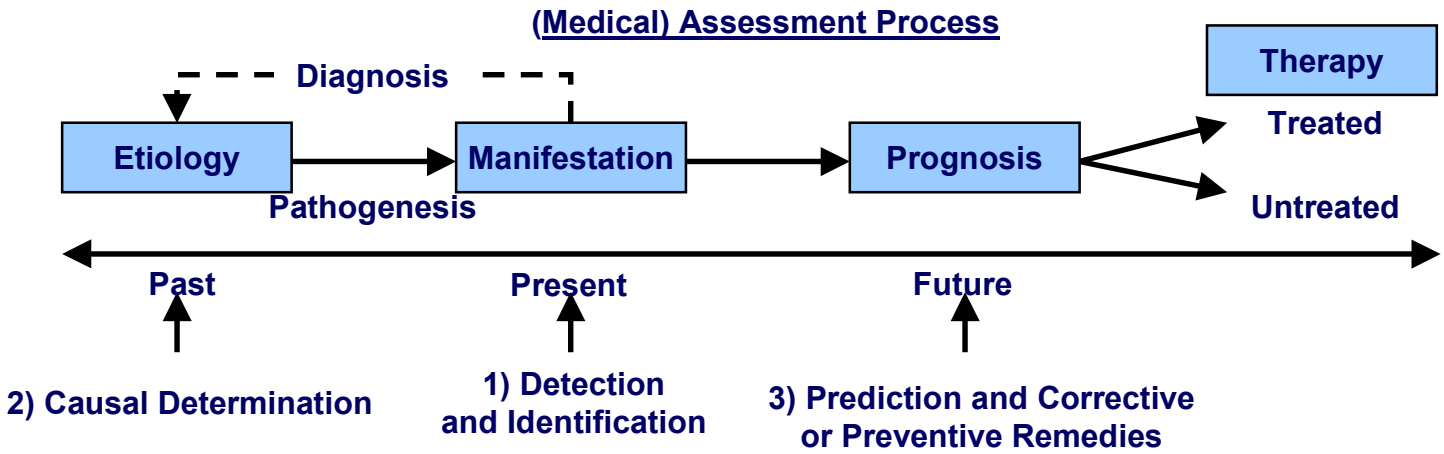


"Engine-1 turbine contacted housing 5.2 seconds after shutdown, lasting 0.2 seconds. Probably caused by overheated pump. No damage evident or expected; no action needed."

☞ Automated detection, identification, diagnosis, prognosis, and recommendation ☜

Knowledge-based Assessment - Process

1) What symptoms are present?
2) What is the nature and origin of symptoms?
3) What might happen and what should be done?



- Launch information more limited than medical; launch only has observations, whereas medical has observation, inquiry, and lab tests.
- Launch observation is complicated: data is noisy, voluminous yet under-sampled/quantized, not precisely time-stamped
- Coordinating multiple knowledge-bases essential, for example systems engineering knowledge with signal processing.

☞ Launch assessment is vehicle health care insurance ☜

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Data, Information, and Knowledge Sources and Representations

- **Data (facts)**
  - Sensor telemetry; databases w/ metadata (sample rates, quantization) and time-series data
  - Mission plans; tables of scheduled events with constraints
- **Information (patterns)**
  - Sensor time-series envelopes; mini-language for specifying rise & decay patterns
  - Family data statistics; computed derived time-series norms
- **Knowledge (reasoning)**
  - Vehicle sub-system behavior and physical constraints; engineering handbook tables and formulas
  - Anomaly assessment experience rules-of-thumb; ad-hoc constraints

☞ Increasing degrees of awareness; multiple mediums ☜

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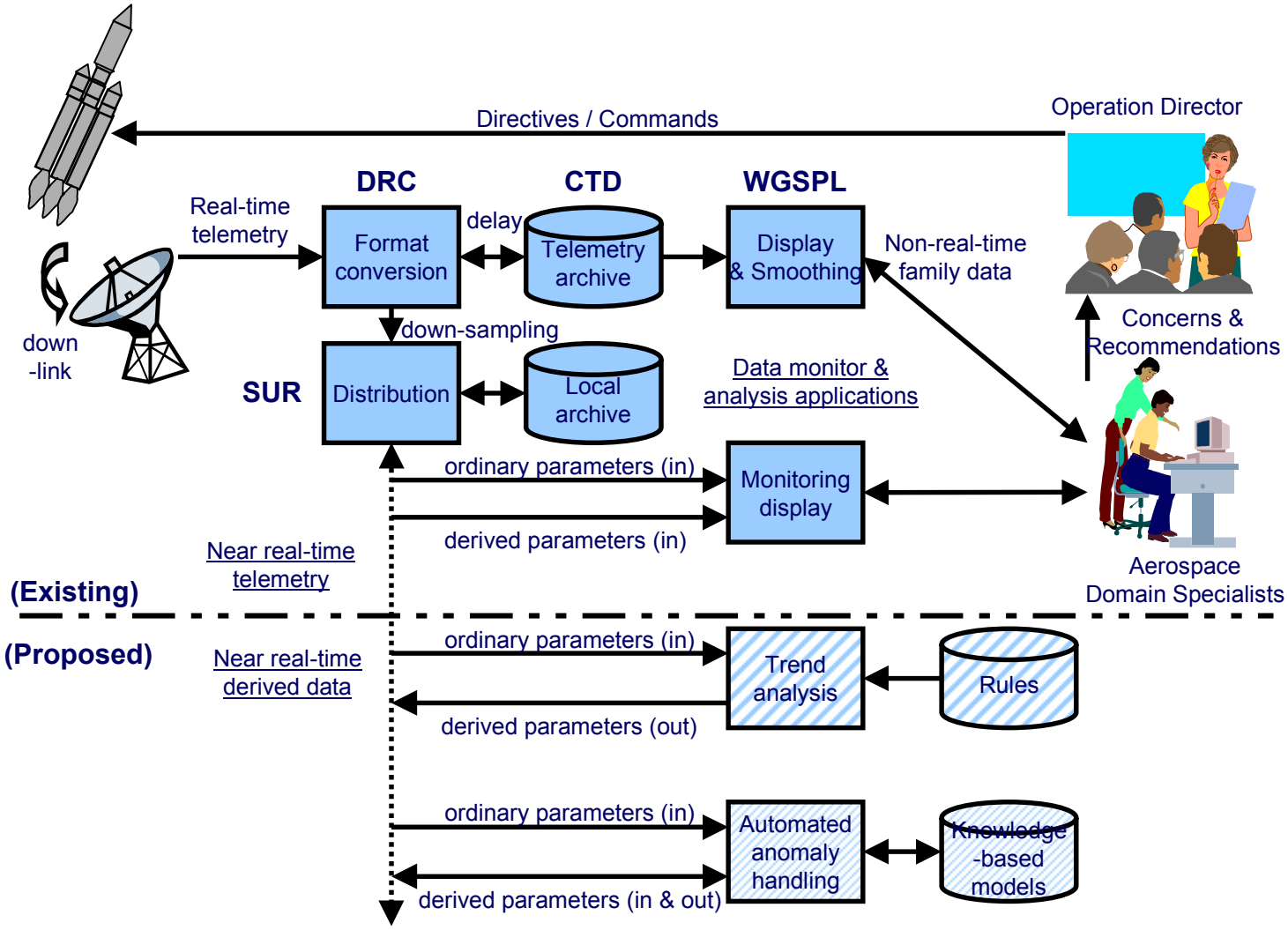
Characteristics of STARS Architecture

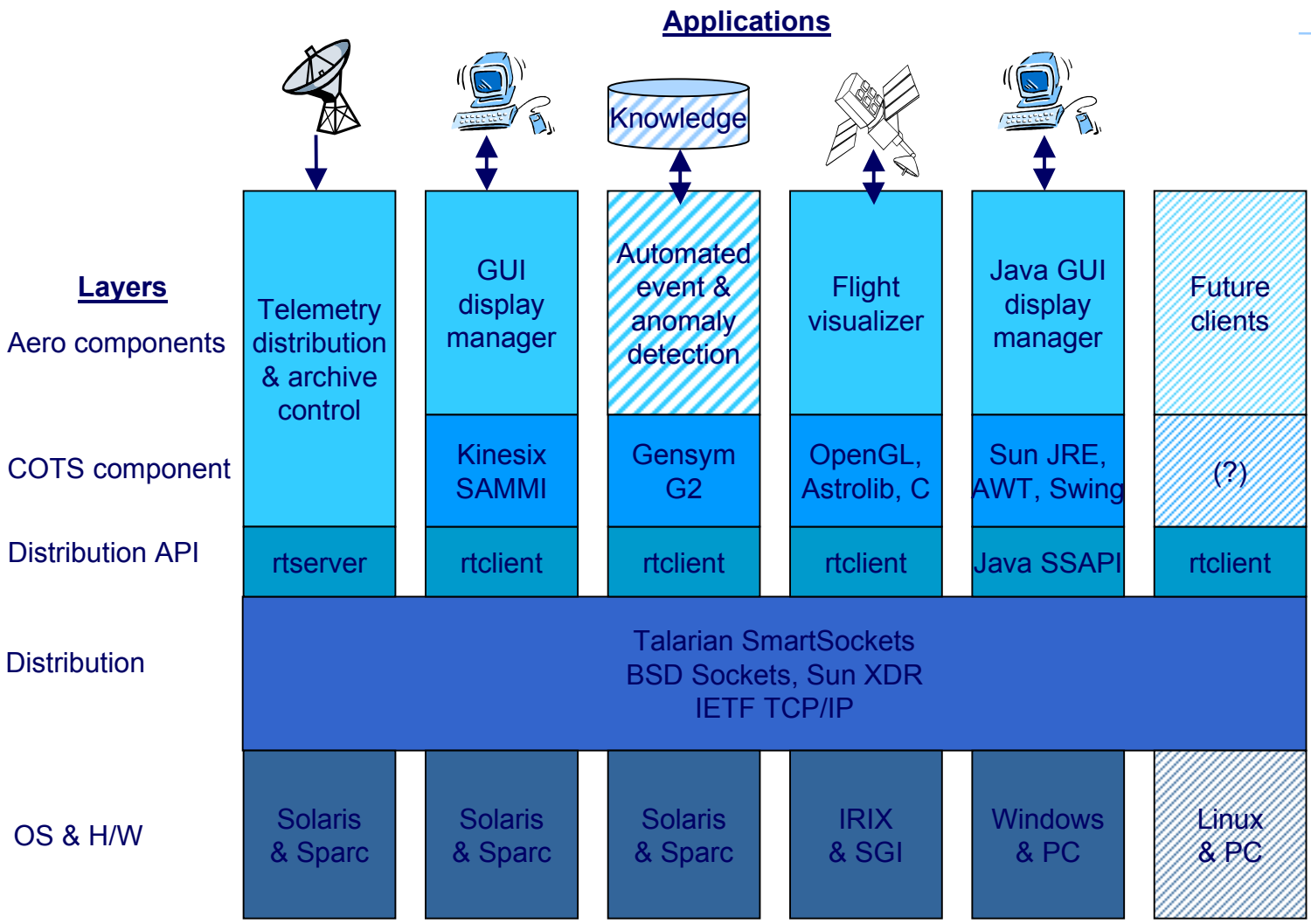
- Human domain-specialists perform simple detection in real-time using electronic plots of sensor values, and plot comparisons for post-flight verification.
- A distributed processing system, enabled by voice and data communications.
- Applications inter-operate via data streams. Sensor data plotting is the primary application; others include scheduled event detection and flight visualization. Applications are implemented using tailored COTS and in-house code.
- Messaging infrastructure built on tailored COTS delivers data to applications using publish/subscribe paradigm and enables “plug-and-play” application modules.
- Real-time data is down-sampled, time-stamped packets from multiple sensors; full-rate archived data is also available.

Component-interface Architecture View



Nested closed-loop plants; incremental extension

Layered-application architecture view



"Plug-and-play"

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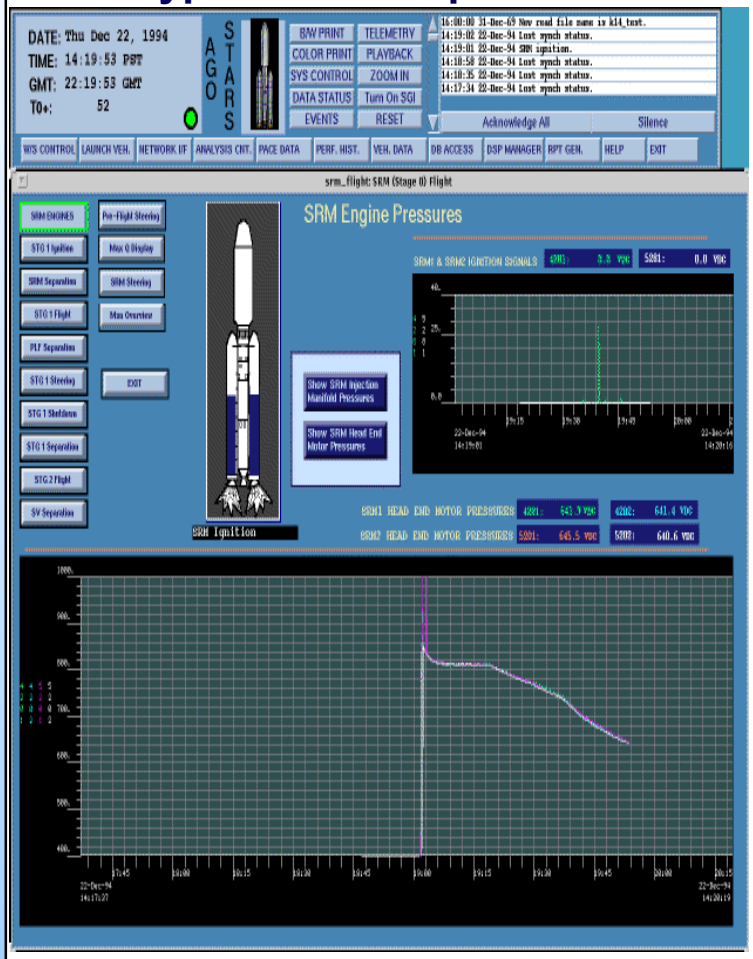
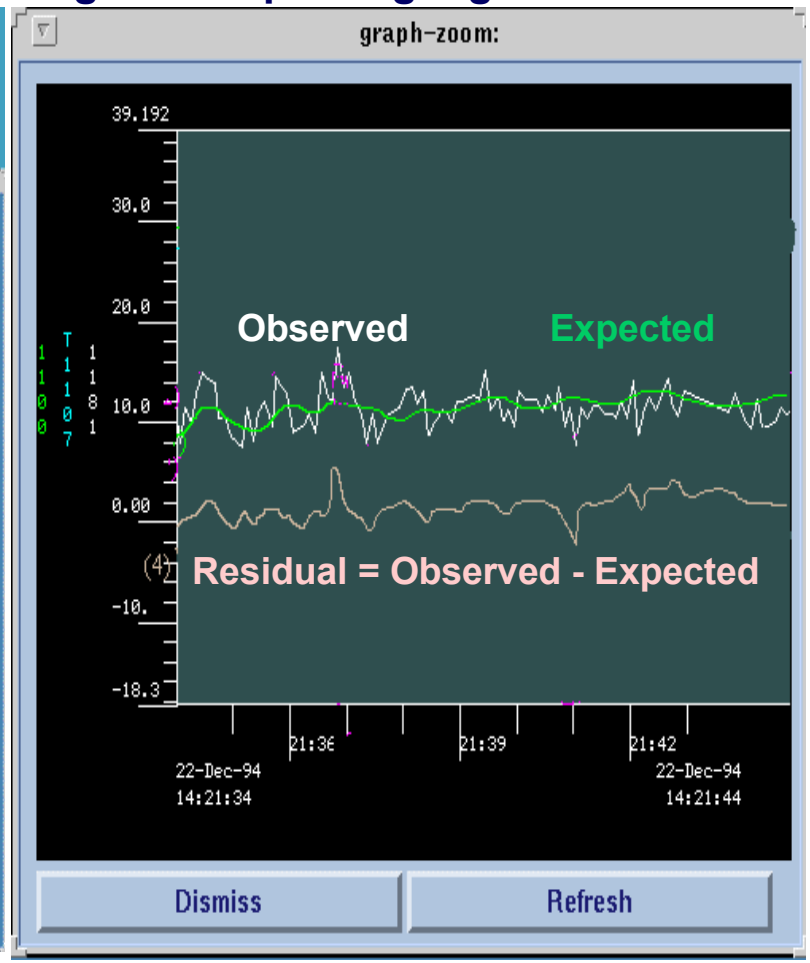
Human-interface Architecture View

Typical STARS plot



Augmented plot highlights deviations



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Knowledge-based Applications - Legacy

- **Neural net based specialized anomaly detection**
  - Training data limited (few examples)
  - Limited identification (specific failures)
  - Inexplicable analysis, non-scalable approach
- **Code and rule based launch event detection**
  - Vehicle-specific, limited generalization of criteria leads to duplication of effort for implementation and maintenance
  - Simplistic, non-robust detection criteria may be inadequate if data is missing or corrupt
- **Integrated anomaly detection and reporting [7]**
  - Hyperlinks report with data

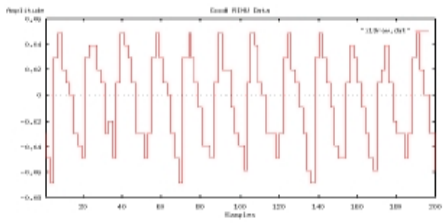
Neural Nets for Recognizing Known Anomalies

Neuralworks tool tailored to distinguish three (3) classes (good, bad, noise) from FFT input using three-layer back-propagation network (taken from [2]).

Neural Nets: Real World Problem

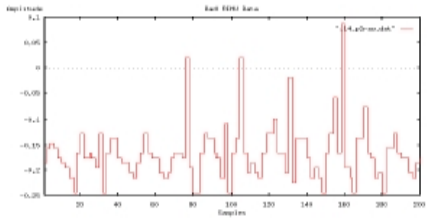
- Failing IUS RIMU (Intertial Guidance Unit) data
  - *Sum Channel voltage showed anomalous behavior before failing*
  - *Anomaly was not discovered launch testing causing expensive delay*

Failing RIMU Data

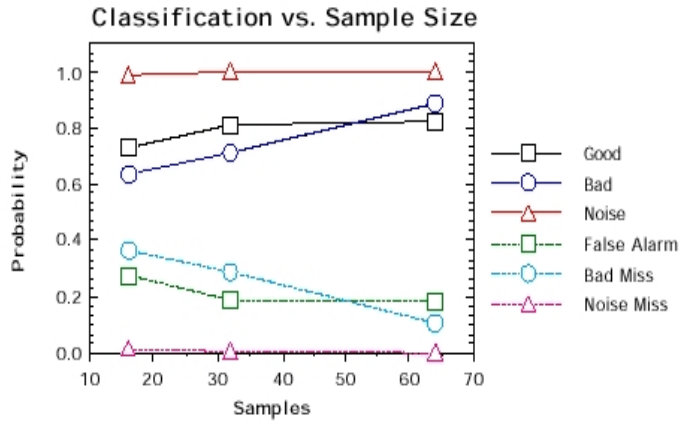


GOOD RIMU

BAD RIMU

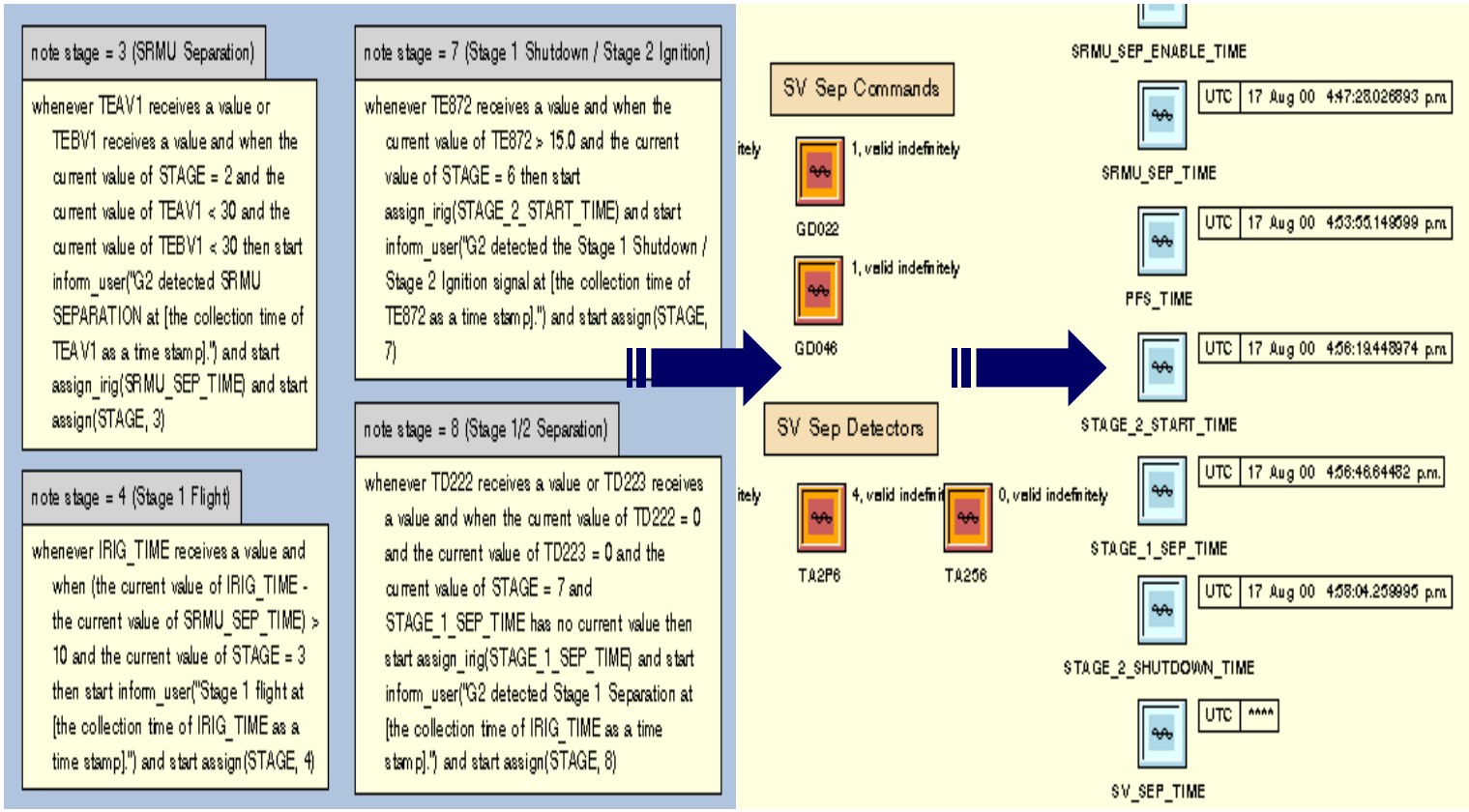


Neural Network Results



Rule-based Launch Event Detection

Gensym's G2 expert system shell tailored (rules at left) to detect Titan scheduled launch events (derived parameter times at far-right) using live telemetry and internal variables (at middle-right).



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Integrated Anomaly Detection and Reporting [7]

UNCLASSIFIED

ISTAR EXPERT SYSTEM

Functions

ISTAR Telemetry Analysis Expert System

Displays

ANOMALY REPORT

QUIT

Mode Control

EXPERT ON

Display Control

GMT 000: 14834 EME 000: 00: 00: 00

UNCLASSIFIED

Anomaly report hyperlinks to telemetry

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Emerging Knowledge-based Automation

- **Enhanced scheduled event and state detection**
  - Expectations based on mission plans and handbooks; parameterized generic plan
  - Reinforcing criteria (time, altitude, acceleration)
  - Feature-based signal envelopes for jitter rejection
- **Enhanced anomaly detection**
  - Expectations based on family norms (expected value, dynamic “red-line” bands)
  - Registered to event weigh-points

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Sample Mission Scheduled Event Plan

Event sequence | Physical basis | Measurand(s) values

Code	Event description	Basis	Detection criteria
Ggi	Guidance go-inertial		
LVlo	Lift-off	2-inch motion	
PFj	Payload Fairing jettison	S1E1j + ? sec	CKR011C from 0 to 1 v in 0.1 ± 0.01 s; for 2 ± 0.2 s; to 0 v in 0.1 ± 0.01 s && CKR051C 0 to 1 v in 0.1 ± 0.01 s; for 2 ± 0.2 s; to 0 v in 0.1 ± 0.01 s
Ss	Spacecraft separation (may be after first or second burn)	{MECO 1 + ? sec} {MEC0 2 + ? sec}	{CKS019C from 0 to 1 v in 0.02 ± 0.002 s; for 0.1 ± 0.01 s; to 0 v in 0.02 ± 0.002 s} {CKS075C from 0 to 1 v in 1 ± 0.1 s; for 0 ± 0.001 s; to 0 v in 1 ± 0.1 s}
S12s	Atlas / Centaur separation	S1E2j	CM_037D from 0 to 15 v in 1.5 ± 0.15 s; for 0.0 ± 0.001 s; to 1.0 ± 1.0 v in 0.2 ± 0.02 s && CKR114C from 0 to 1 v in 0.02 ± 0.002 s; for 0.25 ± 0.025 s; to 0 v in 0.02 ± 0.002 s
S1E1i	Booster ignition	LO - ? sec	
S1E1c	(BECO) Booster cutoff	5.0 g	AM_026D from 0 to 15 v in 0.7 ± 0.1 s; for 0.0 ± 0.001 s; to 2.5 ± 2.5 v in 0.02 ± 0.002 s
S1E1j	Booster jettison	BECO + 3.1 sec	
S1E2i	Sustainer ignition	LO - ? sec	
S1E2c	(SECO/VECO) Sustainer/Vernier c/o	propellant depletion	CKK976X from 0 to 1 v in 8.0 ± 1.0 s; for 0 s; to 1 v in 0 s
S1E2j	Sustainer jettison	SECO + 2 sec	
(S1E3l)	GL SRM pair ignition	LO – 0.51 sec	
(S1E3c)	GL SRM pair declared burnout	Sense acceleration drop + filter delay + Δ-t1	
(S1E3j)	GL SRM pair jettison	M > 1.2 & t > S1E4l + 3 sec	
(S1E4l)	AL SRM pair ignition	S1E3c + ? sec	
(S1E4c)	AL SRM pair burnout	Sense acceleration drop + filter delay + Δ-t2	
(S1E4j)	AL SRM pair jettison	S1E4c + ? sec	
S2E1i1	(MES 1) Centaur first burn	SECO + 18.5 sec	CKS081C from 0 to 1 v in 0.0 ± 0.1 s; for 0 s; to 1 v in 0 s
S2E1c1	(MECO 1) Centaur first cutoff	initiated by INU when parking orbit achieved	
S2E1i2	(MES 2) Centaur second burn	initiated by INU when trajectory correct	
S2E1c2	(MECO 2) Centaur second cutoff	initiated by INU when trajectory correct	
S1m1b	Roll program start	LO + 8 sec	
S1m1e	Roll program stop	LO + 15 sec	
S2m1b	Attitude align & spin start		
S2m1e	Attitude align & spin stop		

☞ Launch event/state ontology, formal criteria specification ☜

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Mission Event Reporting

discrete_event_list4:

PRINT

Titan IV B34 Mission Event List
STAGE 2 FLIGHT EVENTS

EXIT

Event	Value / Status		Predicted Time	Actual Time
Enable Stage 2 Shutdown	(FTS DISC STAGE 2 S/D ENABLE RELAY A IND - TD260)		0.00	0.00
(TD286 ON) OFF				
(TD394 ON) OFF	STG2 S/D ENABLE RLY A - TD260	0		
	STG2 S/D ENABLE RLY B - TD261	0		
**** STAGE 2 COMMAND SHUTDOWN ****			(GCU DISCRETE #13)	0.00 0.00
Enable Stage 2 FTS Safing			(GCU DISCRETE #18)	0.00 0.00
(GD013 ON) OFF (GD018 ON) OFF	STG2 SHUTDOWN RLY A	0	(GCU DISCRETE #37)	0.00 0.00
(GD037 ON) OFF (GD042 ON) OFF	STG2 SHUTDOWN RLY B	0	(GCU DISCRETE #42)	0.00 0.00
Stage 2 FTS Safing				
(GD019 ON) OFF	STG2 FTS SAFING RLY A	0	(GCU DISCRETE #19)	0.00 0.00
(GD043 ON) OFF	STG2 FTS SAFING RLY B	0	(GCU DISCRETE #43)	0.00 0.00
Stage 2 Retro Rockets On/Off				
(GD020 ON) OFF (GD021 ON) OFF		Retros On	(GCU DISCRETE #20)	0.00 0.00
(GD044 ON) OFF (GD045 ON) OFF			(GCU DISCRETE #44)	0.00 0.00
		Retros Off	(GCU DISCRETE #20)	0.00 0.00
			(GCU DISCRETE #44)	0.00 0.00
***** SV SEPARATION ********			(GCU DISCRETE #22)	0.00 0.00
			(GCU DISCRETE #46)	0.00 0.00
(GD022 ON) OFF (GD023 ON) OFF				
(GD046 ON) OFF (GD047 ON) OFF				

Stg 2 Long Truss Accels
1.0
0.
-1.
00:10 00:20 00:30
31-Dec-69 16:00:00
31-Dec-69 16:00:37

☞ Highlight actual exceptions to predicted ☜

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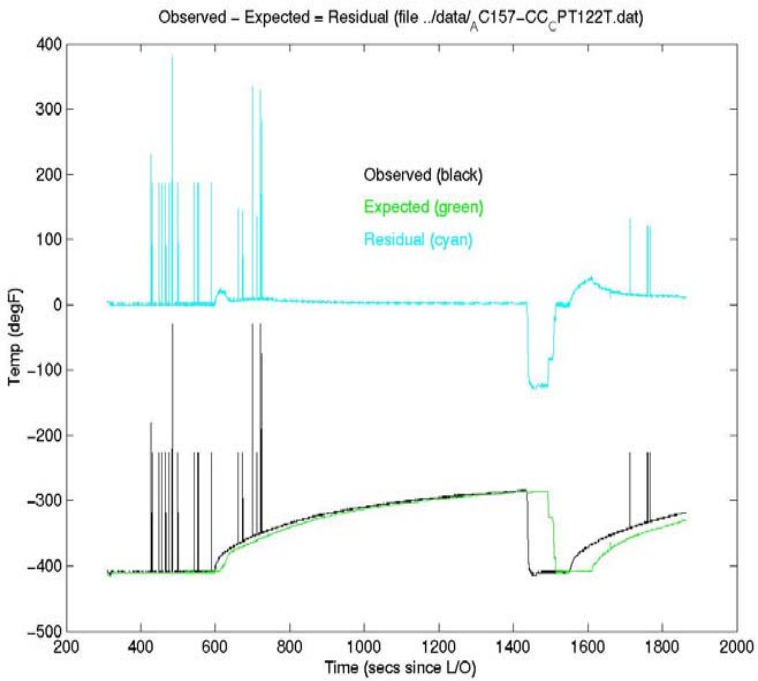
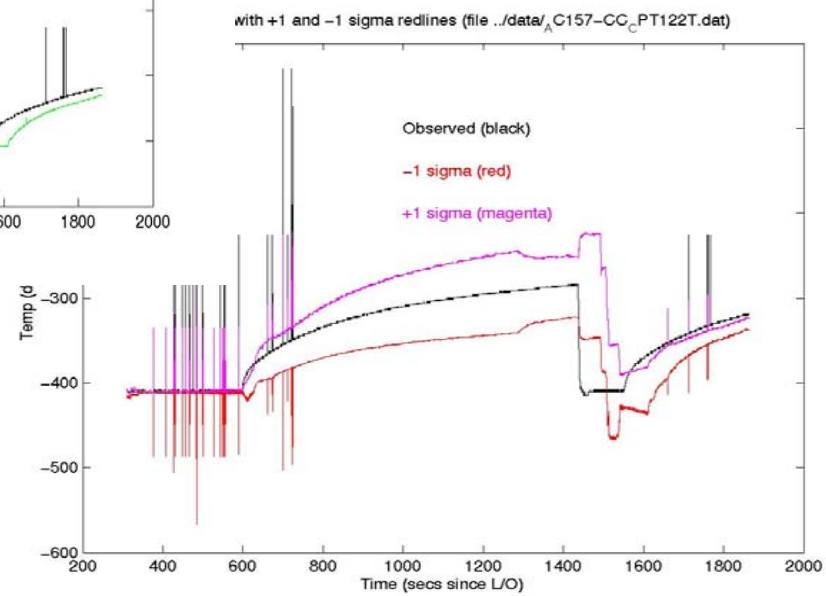
Applying Family Statistics Models





☞ Highlight exceptions to statistical norms ☜

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Conjectured Knowledge-based Automation

- **Advanced Knowledge-based Anomaly Analysis**
  - Augments and corroborates statistical analysis
  - Model-based reasoning
  - Anomaly detection
  - Anomaly diagnosis
- **Decision support for people**
  - Provide recommendations for corrective and preventive action (sometimes just leave it be)
  - Depends on good diagnosis, which depends on good identification
- **No monolithic tool**
  - Generic and specialized (broad) model-based expert systems
  - Coordinated expert systems
  - Synthesized views composed from vehicle subsystems models

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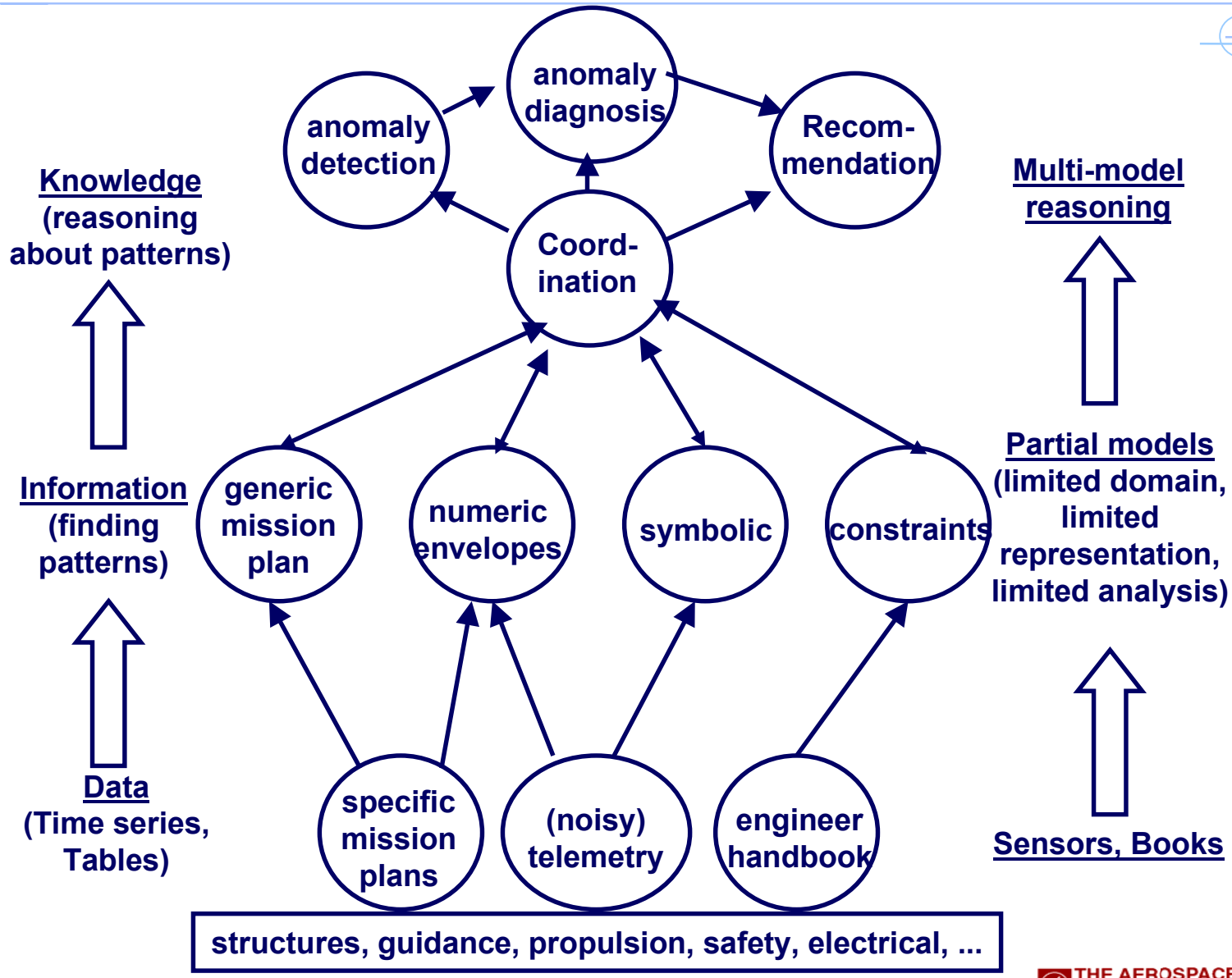
Key Knowledge-based Assessment Elements



Example Coordinated Knowledge-based Models

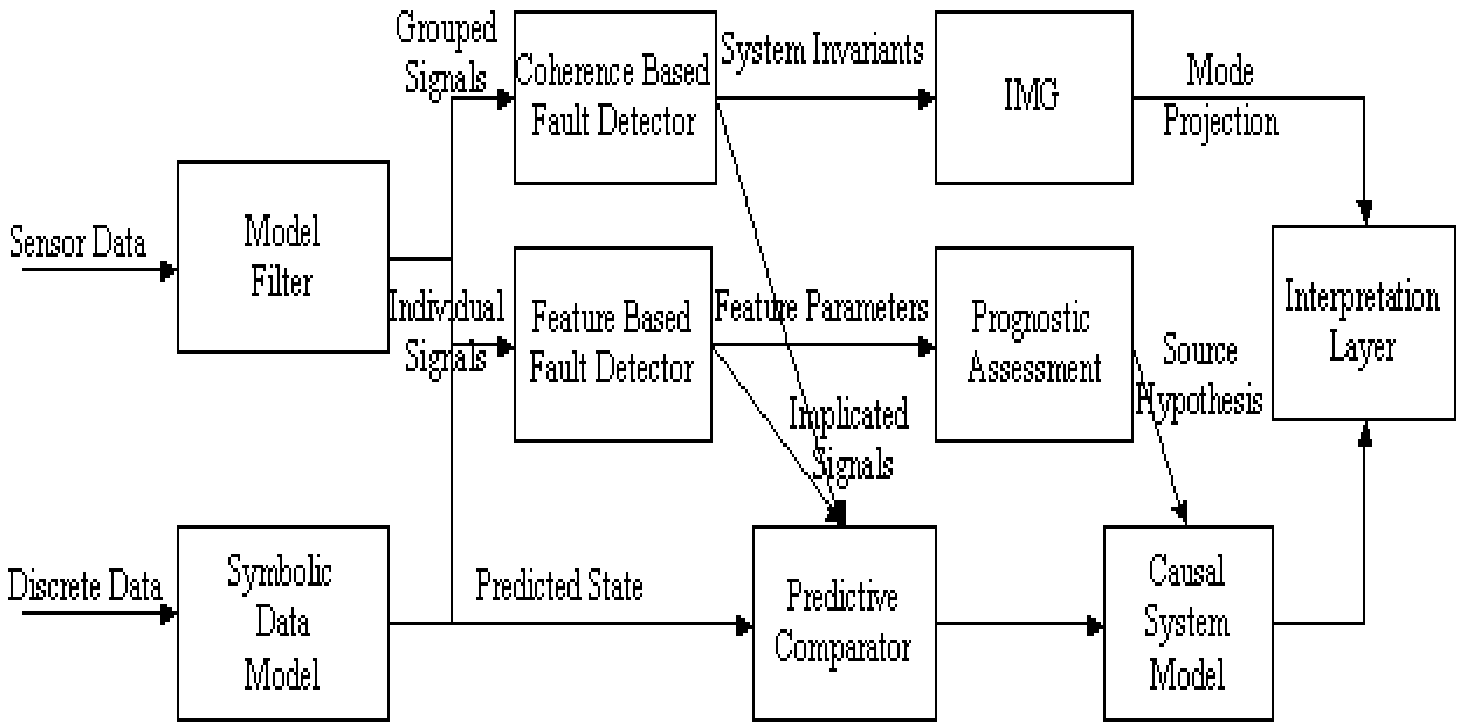


Figure 1: Top-Level BEAM Architecture (taken from [6])

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Conclusions and ...

- **Real-world operations**
  - Too much data, not enough information (noise, lack of time-stamps, down-sampled data, lack of telemetry standards (but see [1]))
  - People (clever pattern recognizers, but error-prone; they don't know what they know)
  - Extensible, data-centric architecture enable unobtrusive technology insertion (not just for plotting!)
- **Trouble, yes sir, right here in River City**
  - Where have all the people gone?
  - What, more launches?
  - Future shock (better, faster, cheaper)
- **Successes, more or less**
  - We've learned some things about what doesn't work
  - We've learned some things about what works
  - We've learned some things about what could work

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… and Challenges

- **No single technique is a "magic bullet"**
  - Distinguishing signals (events and anomalies) masked by noise requires both numeric and symbolic analysis
  - Coordination of multiple knowledge sources and techniques is essential for robust detection and diagnosis
  - Trade space (and pre-processing time) for time
- **Model-based reasoning offers a solid foundation**
  - Has been used successfully for automated anomaly detection and diagnosis in production systems
  - Multiple models provide a variety of perspectives on vehicle health and status, offering a more comprehensive view than any single-model approach.
- **Need sophisticated coordination techniques (~ voice)**
  - Need to codify expert knowledge from unpublished sources
  - Need more robust numerical, signal processing, statistical analysis, and fuzzification
  - Need synchronization with logical, discrete, and modal analysis

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