STOCHASTIC APPROACH TO SPACECRAFT THERMAL CONTROL SUBSYSTEM

Why?

- Scatter on physical parameters
  - Thermo-optical properties
  - Contact conductances
  - Handling process
  - Density
- Scatter on environment parameters
  - External fluxes
  - AOCS
- Scatter on interface definition
  - Units power dissipation
  - Harness

STOCHASTIC APPROACH TO SPACECRAFT TCS

How?

- Creating a Mother mathematical model
- Selecting input parameters and giving them a variation law
- Selection of a combination of input values with the Monte Carlo methodology
- Cloning the Mother model for each set of input variables combination
- Running deterministic cases with a cloned model per combination

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STOCHASTIC APPROACH TO SPACECRAFT TCS

What?

- Thermal Problems on Spacecraft
  - Radiation and conduction
- Fluid Systems
  - CPL and Loop Heat Pipes (bubbles, non-homogenous wicks, ...)
- Launchers Aerothermal Fluxes
  - Angle of attack, density,…
- Reentry Vehicles
  - Angle of attack, density,...

STOCHASTIC APPROACH TO SPACECRAFT TCS

Thermal problems on spacecraft solved by STORM

Stochastic Problems

- Uncertainty analysis
- Correlation of test results
- Design improvements

Non Stochastic Problems

- Critical design cases selection
- Definition of designs
  - Radiation areas
  - Robust heating systems

STOCHASTIC APPROACH TO SPACECRAFT TCS

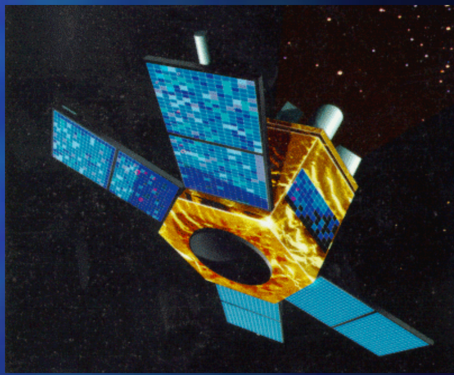
Uncertainty analysis of a satellite

- Typical Uncertainty Analysis
  - Steady State
  - Transient
- Output is the temperature of an item (i.e. equipment) by combining all input parameters simultaneously
- Identification of highly sensible parameters in order to propose, if necessary, a specific development test or interface control follow-up
- Definition of maximum uncertainty
- Definition of uncertainty with levels of confidence (98%, 95% or 90%) in one run

STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- Example: Spanish MINISAT equipment response varying:
  - Absorptivity of the rear frame
  - Emittance of rear frame
  - MLI shape factor (2 to 7)
  - Power dissipation of units (±20%)

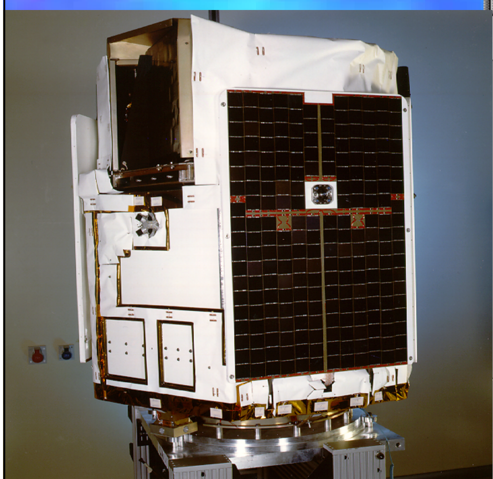


Note: All input variables have uniform distribution.
Initial phase for uncertainty analysis.
In the final project phase the distributions will be changed to Normal or Uniform distribution, as defined

STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- SIGNIFICANT INPUT VARIABLES



STATS: sensinew.PRJ

File Functions Ant-Hill Windows Tools

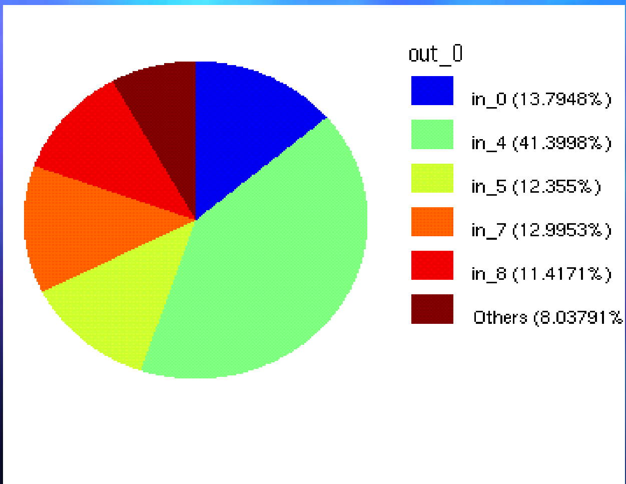
Independent Input Variables: 9	Shot: 1
in_0 --> ALPHA Rear Frame CLEAR ANOD.	0.39
in_1 --> ALPHA Rear Frame CHROMIC ANOD.	0.38
in_2 --> EPSILON Rear Frame CLEAR ANOD.	0.89
in_3 --> EPSILON Rear Frame CHROMIC ANOD.	0.6
in_4 --> MLI FACTOR	2
in_5 --> OBDH POWER	23
in_6 --> TRP POWER	8.35
in_7 --> PCU POWER	12.52
in_8 --> MW POWER	4.3

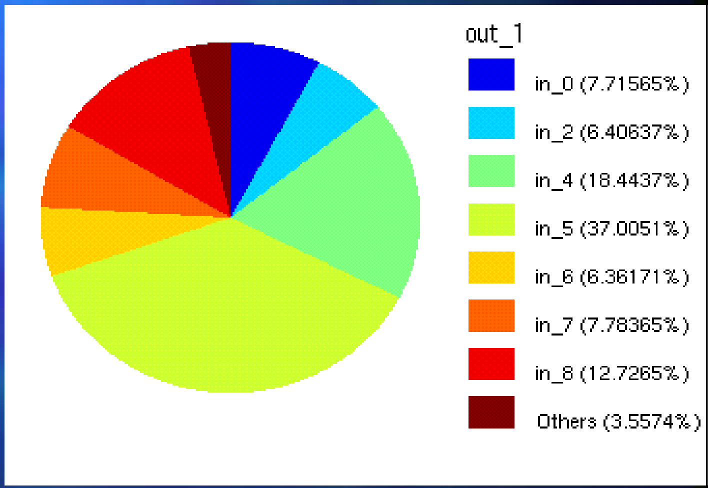
Output Variables: 4	Shot: 1
out_0 --> Batt Temp	6.78
out_1 --> OBDH Temp	27.07
out_2 --> TRP Temp	19.42

STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- SIGNIFICANT INPUT VARIABLES





MLI Factor the most significant for the Battery

The Power and MLI factor the most significant for the OBDH

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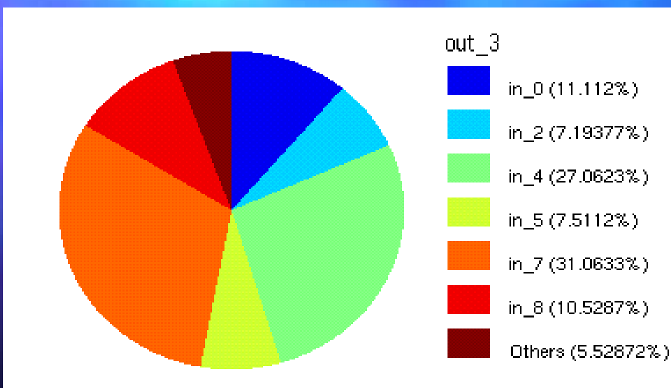
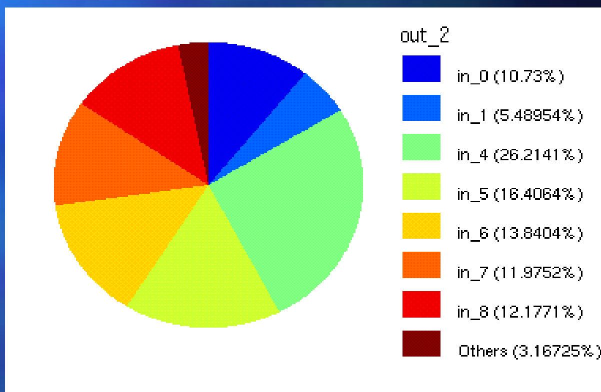
Uncertainty analysis of a satellite (cont.)

- SIGNIFICANT INPUT VARIABLES





MLI Factor and its Power the most significant for the PCU

The Power of OBDH, its Powerand MLI factor the most significant for the TRP

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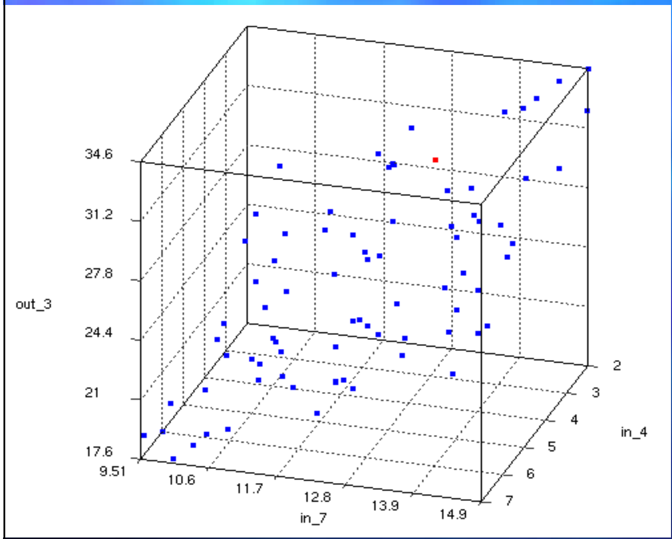
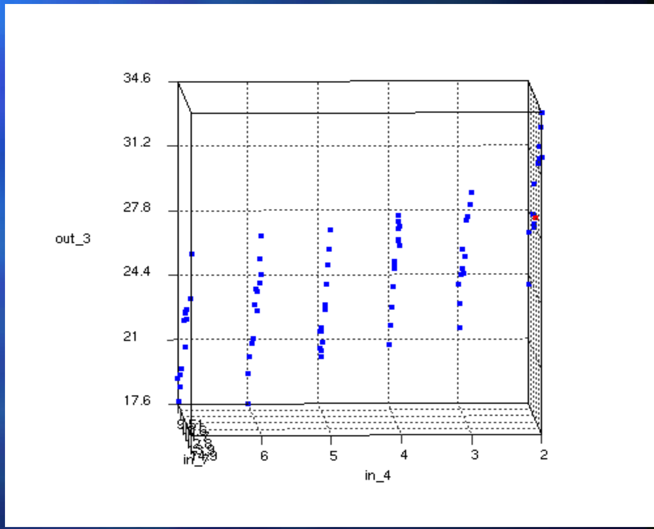
STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- SIGNIFICANT INPUT VARIABLES





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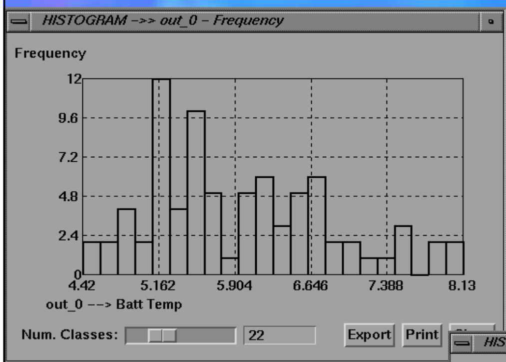
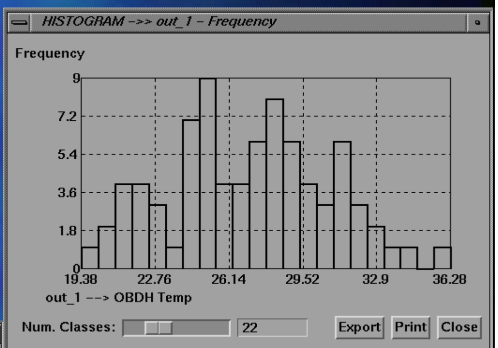
STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- PROBABILISTIC DATA OF UNCERTAINTY ANALYSIS

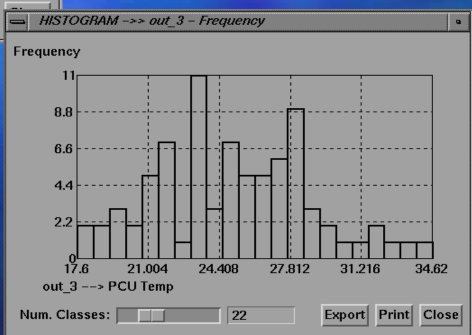


PCU profile



Batt profile

OBDH profile



STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- PROBABILISTIC DATA OF UNCERTAINTY ANALYSIS

N.Var	Num. shots	X_Min	X_Max	Conf_Mean-	Mean	Conf_Mean+	Conf_Std-	Std	Conf_Std+	Var
in_0	80	0.37	0.42	0.391	0.395	0.399	0.015	0.0174	0.0206	0.0003
in_1	80	0.35	0.44	0.389	0.395	0.401	0.0238	0.0275	0.0325	0.00075
in_2	80	0.87	0.91	0.887	0.89	0.893	0.0123	0.0142	0.0169	0.0002
in_3	80	0.4	0.7	0.538	0.553	0.567	0.0584	0.0675	0.0799	0.00455
in_4	80	2	7	4.11	4.49	4.86	1.48	1.71	2.03	2.94
in_5	80	20	30	24.4	25	25.6	2.5	2.89	3.42	8.33
in_6	80	8.01	10.9	9.28	9.48	9.67	0.754	0.872	1.03	0.76
in_7	80	9.51	14.9	11.9	12.2	12.6	1.41	1.63	1.93	2.66
in_8	80	4	6.9	5.25	5.45	5.64	0.765	0.884	1.05	0.782
out_0	80	4.42	8.13	5.76	5.96	6.15	0.774	0.895	1.06	0.8
out_1	80	19.4	36.3	26.2	27	27.9	3.2	3.7	4.38	13.7
out_2	80	12.9	25.9	18.1	18.7	19.3	2.32	2.68	3.18	7.19
out_3	80	17.6	34.6	24.3	25.1	25.9	3.26	3.76	4.46	14.2

STOCHASTIC APPROACH TO SPACECRAFT TCS

Uncertainty analysis of a satellite (cont.)

- PROBABILISTIC DATA OF UNCERTAINTY ANALYSIS

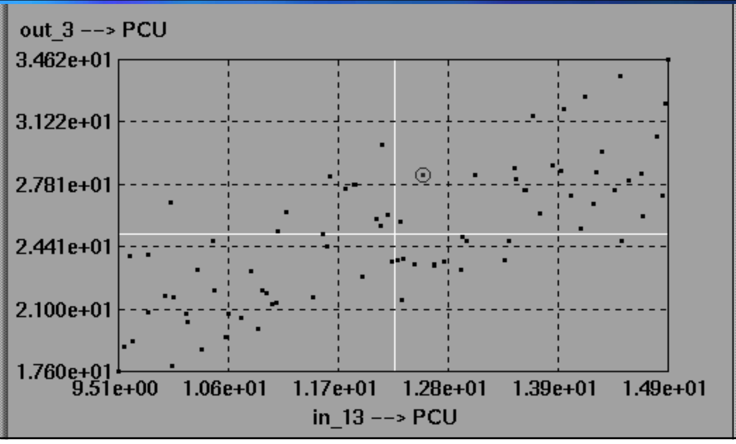
N.Var	Modal class-	Modal class+	CV(%)	Avdev	Skewness	Kurtosis	Description
in_0	0.407	0.414	4.4	0.0152	-0.0219	-1.31	ALPHA Rear Frame CLEAR A.
in_1	0.35	0.361	7	0.024	-7.47E-06	-1.24	ALPHA Rear Frame CHROMIC A.
in_2	0.87	0.875	1.6	0.012	-7.55E-06	-1.3	EPS Rear Frame CLEAR ANOD.
in_3	0.475	0.512	12.2	0.06	0.158	-0.246	EPS Rear Frame CHROMIC AN.
in_4	2	2.62	38.2	1.49	-0.00899	-1.24	MLI FACTOR
in_5	25	26.2	11.5	2.45	-0.00318	-1.12	OBDH POWER
in_6	9.82	10.2	9.2	0.768	-0.0243	-1.3	TRP POWER
in_7	11.5	12.2	13.3	1.39	0.00353	-1.22	PCU POWER
in_8	4.36	4.72	16.2	0.765	0.00477	-1.27	MW POWER
out_0	4.88	5.35	15	0.742	0.558	-0.399	Batt Temp
out_1	27.8	29.9	13.7	3.05	0.0917	-0.621	OBDH Temp
out_2	17.8	19.4	14.3	2.07	0.408	0.226	TRP Temp
out_3	21.9	24	15	3.05	0.238	-0.348	PCU Temp

Uncertainty analysis of a satellite (cont.)

- PROBABILISTIC DATA OF UNCERTAINTY ANALYSIS

			90% Confidence level		95% Confidence level		99% Confidence level	
	Mean	Std	Uncer	Tmax	Uncer	Tmax	Uncer	Tmax
Batt Temp	**5.96**	0.895	1.48	**7.44**	1.75	**7.71**	2.51	**8.47**
OBDH Tem	**27**	3.7	6.12	**33.12**	7.25	**34.25**	10.40	**37.40**
TRP Temp	**18.7**	2.68	4.43	**23.13**	5.25	**23.95**	7.53	**26.23**
PCU Temp	**25.1**	3.76	6.22	**31.32**	7.37	**32.47**	10.57	**35.67**

- PCU RESULTS



Critical cases selection

- Critical Cases Selection based on temperatures for a fixed design and not based on environments
  - Steady State
  - Transient
- All thermal parameters (Radiation data, heat inputs and thermal model) can be changed
  - Orbit altitude, inclination, ascending node…
  - Satellite attitude
  - External Radiation values (solar, albedo, terrestrial)
  - Season
  - Conductances

Critical cases selection (cont.)

- Thermal Capacities
- Heating Power and/or thresholds
- Unit power dissipation (sunlight/eclipse)

Note:

- *THERE IS A CRITICAL CASE FOR EACH UNIT OR SATELLITE ELEMENT*
- *CRITICAL CASES SELECTION DEPENDS ON THE RESPONSE OF THE DESIGN, NOT ON THE INPUTS*

Critical cases selection (cont.)

- Example: Spanish MINISAT. 3 years of flight .
  - Radiators on lateral faces
  - Sun pointed (Nutation up to 7 degrees)
  - Attitude around sun axis 0÷360°. YAW angle
  - Orbit inclination 150° (any ascending node)

  - Note: Any combination of orbit ascending node, season and satellite attitude is feasible depending on launch day.

Critical cases selection (cont.)

- Example: Spanish MINISAT. 3 years of flight .

Variables List

Input Variables: 3

```
in_0 --> yaw angle
in_1 --> ancending node *10
in_2 --> month
```

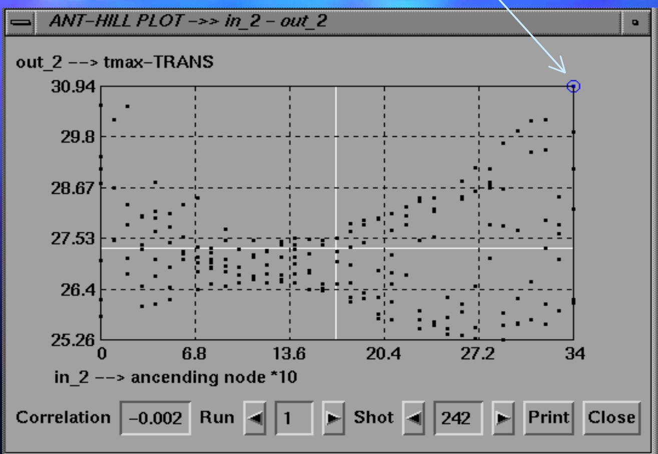
Output Variables: 9

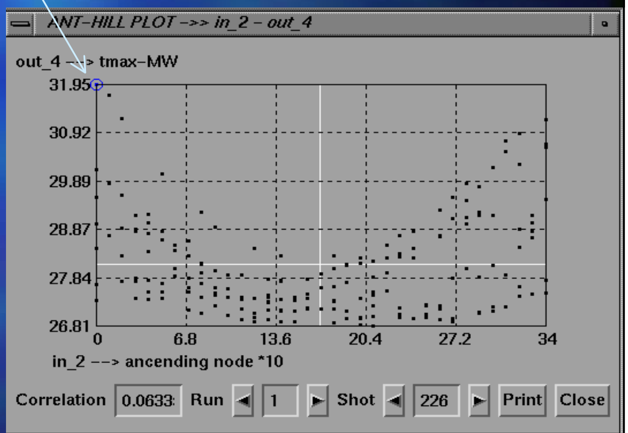
```
out_0 --> tmax-bat
out_1 --> tmax-OBDH
out_2 --> tmax-TRANS
out_3 --> tmax-PDU
out_4 --> tmax-MW
out_5 --> tmax-EMW
out_6 --> tmax-sunsensor
out_7 --> tmax-PCU
out_8 --> tmax-panelsolar
```


Critical cases selection (cont.)

– Transponder Y OBDH
Tmax 30.94°C
Yaw 178 °
Ascen node 340
Season December

– MW, Battery, PCU, PDU and EMW
Tmax 31.95°C
Yaw 107 °
Ascen node 0
Season December





STOCHASTIC APPROACH TO SPACECRAFT TCS

Critical cases selection. "LESSONS LEARNED":

- 0° and 180° rotation w.r.t. Sun pointing vector based on max/min external heat inputs identified during system study (**Classical** Environmental critical cases selection) .
- A stochastic analysis for critical cases selection based on temperatures shows unexpected more extreme temperature profiles for YAW angles of 178 and 107. Flight data confirms this new critical case.
- For other satellite units additional critical cases were found. Stochastic analysis supplies more information for accurate determination of critical design cases.

STOCHASTIC APPROACH TO SPACECRAFT TCS

Thermal test correlation

Present Approach

- Check temperature deviations
- Select a parameter. Modify model
- Verify the response for all thermocouples
- Select other parameter. Modify model
- New runs and verification of results
- Repeat process to meet correlation criteria
- Total analysis loop working time in weeks to months

Stochastic Approach

- Definition of main parameters related to heat transfer in the model. **CORRELATION MATRIX**
- Selection of parameters variation range and interval to move their range.
- Run all test cases imposing objectives
- Verification of feasible correlation results.
- Local problems solution
- Total analysis working time in days

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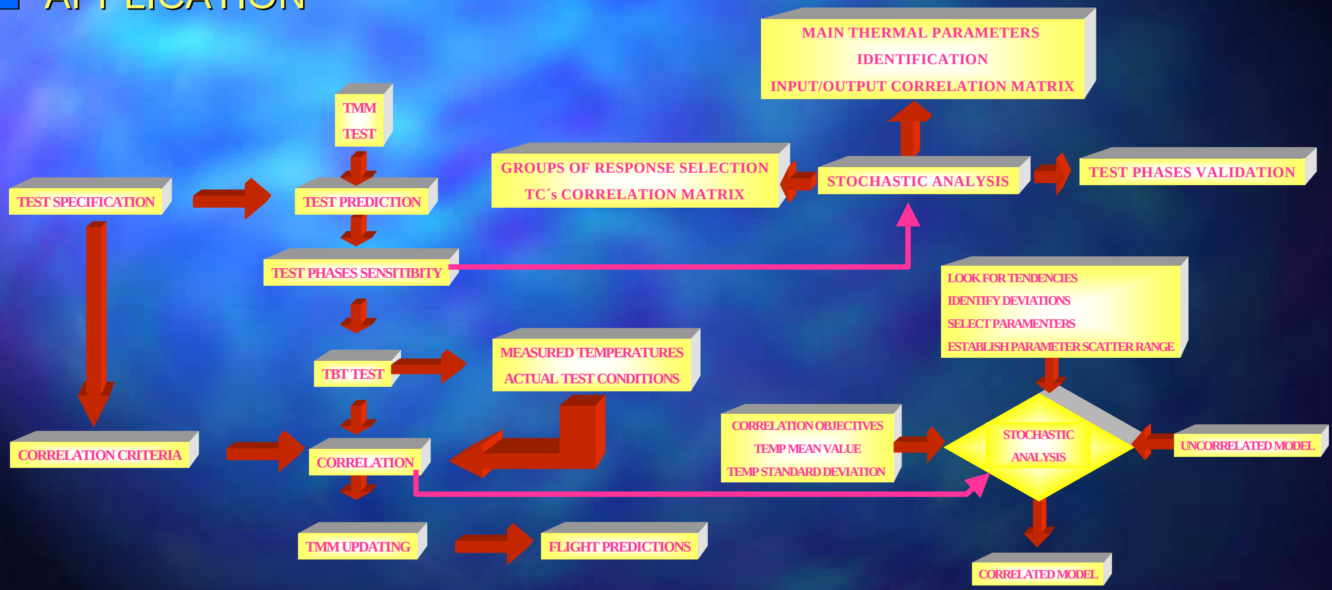
STOCHASTIC APPROACH TO SPACECRAFT TCS

TEST RESULTS CORRELATION & FLIGHT PREDICTIONS. PHASE C/D

- APPLICATION



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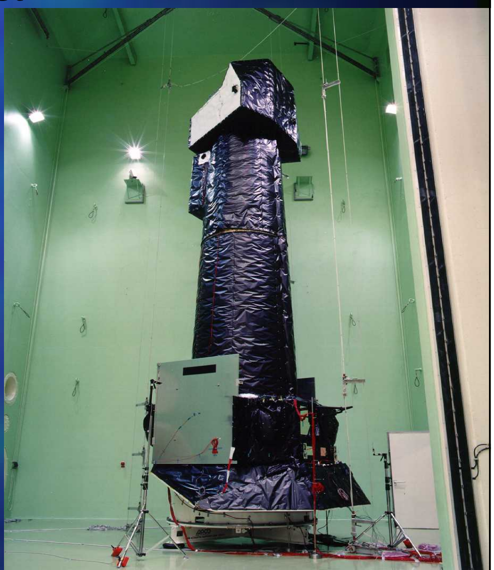
STOCHASTIC APPROACH TO SPACECRAFT TCS

Thermal test correlation (cont.)

- Example of XMM-MSP thermal balance test

  Temperature depends on three main parameters (Conductance to SVM, MLI conductance, Closing foil internal emittance)



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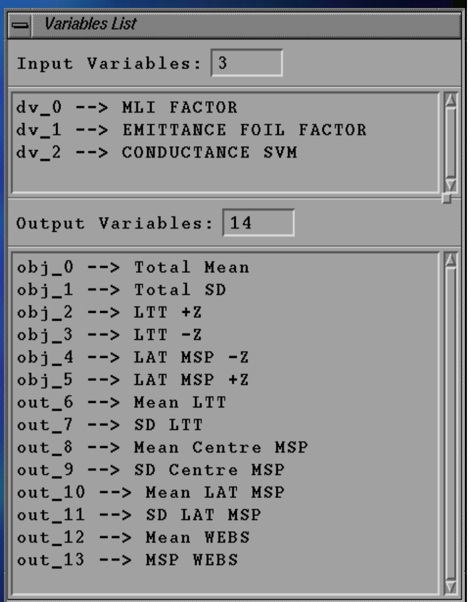
Thermal test correlation (cont.)

- Test correlation requirements
  - Mean deviations lower than 2 degrees.
  - Standard deviation lower than 3 degrees.
  - Critical elements deviation lower than 5 degrees.

STOCHASTIC APPROACH TO SPACECRAFT TCS

Thermal test correlation (cont.)

- Test correlation requirements
  - Mean deviations lower than 2 degrees.
  - Standard deviation lower than 3 degrees.
  - Critical elements deviation lower than 5 degrees.



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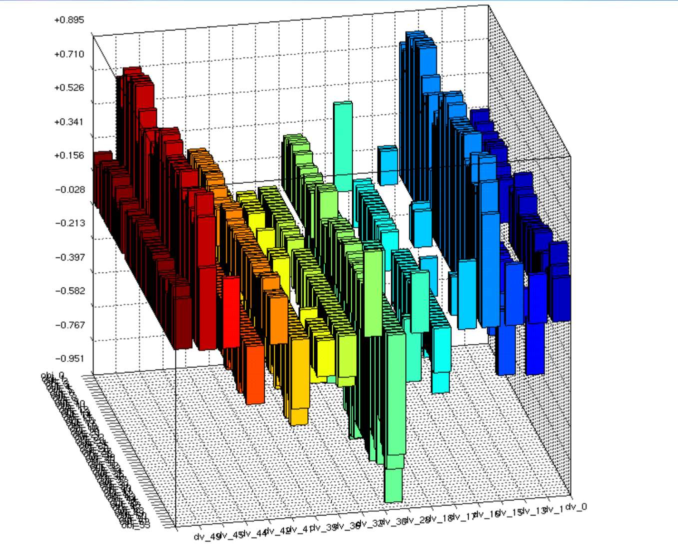
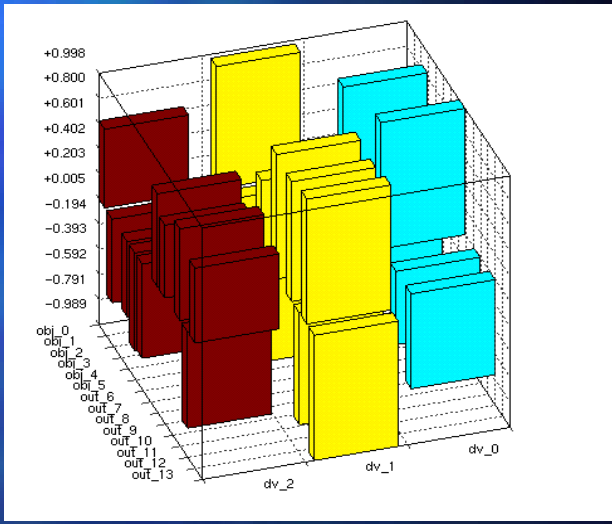
Thermal test correlation (cont.)

- EVALUATION OF SIGNIFICANT INPUT PARAMETERS





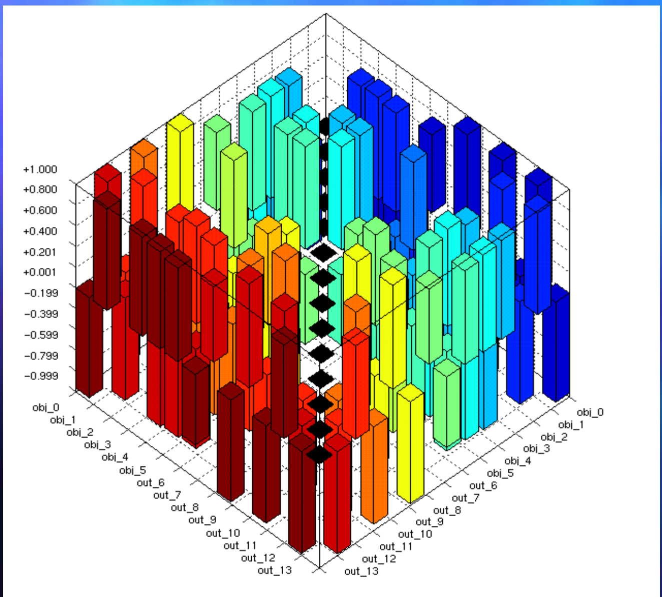
- Global correlation matrix

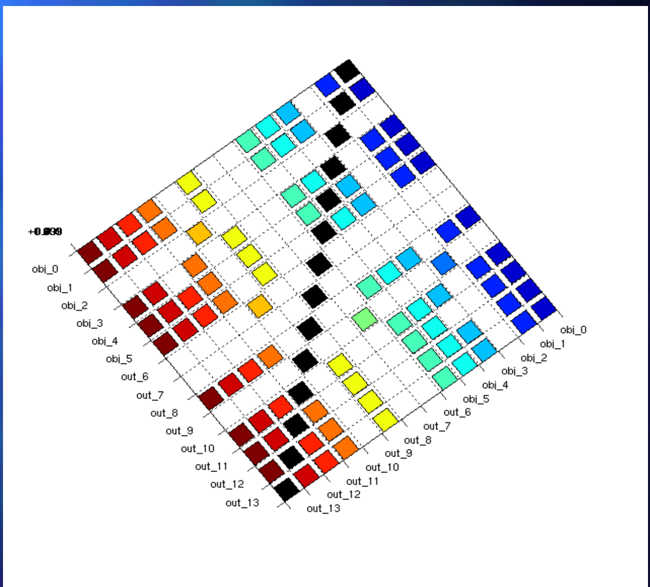
Main significant parameters

STOCHASTIC APPROACH TO SPACECRAFT TCS

Thermal test correlation (cont.)

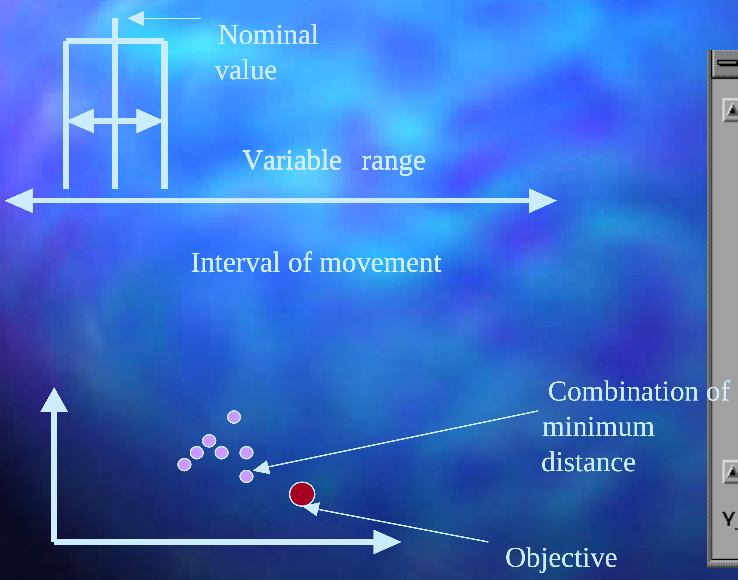
- MAIN OUTPUT CORRELATION MATRIX. GROUPS OF RESPONSE

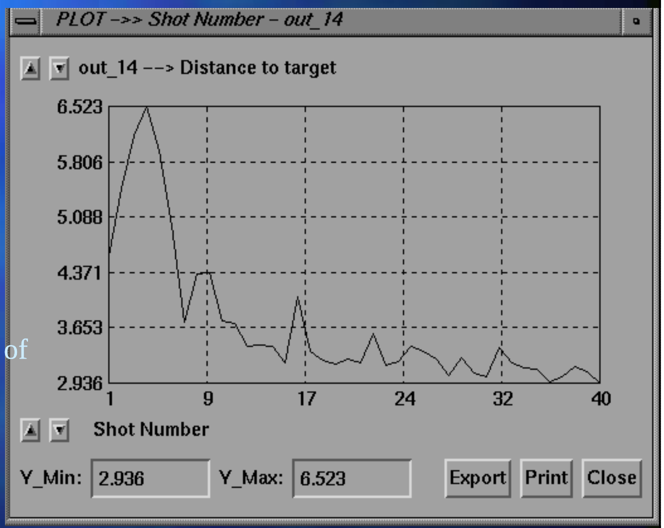




Thermal test correlation (cont.)

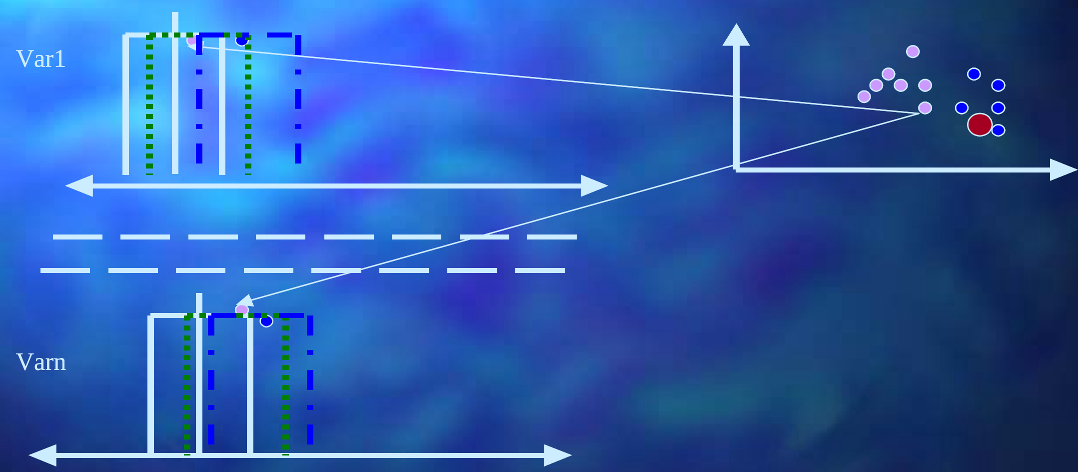
- CORRELATION EXERCISE IMPOSING OBJECTIVES





Thermal test correlation (cont.)

- CORRELATION EXERCISE IMPOSING OBJECTIVES



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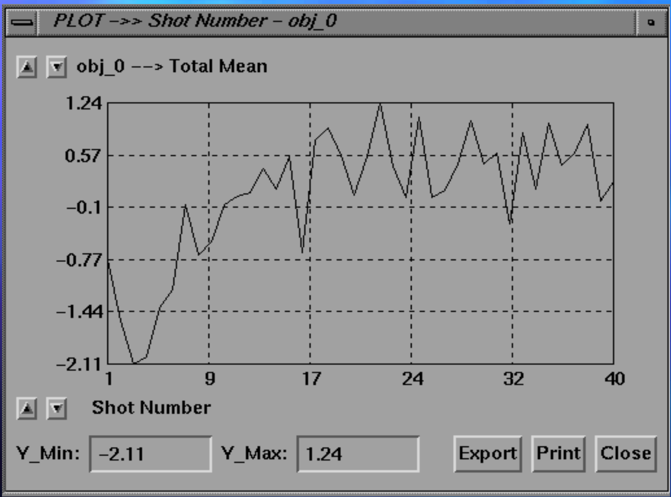
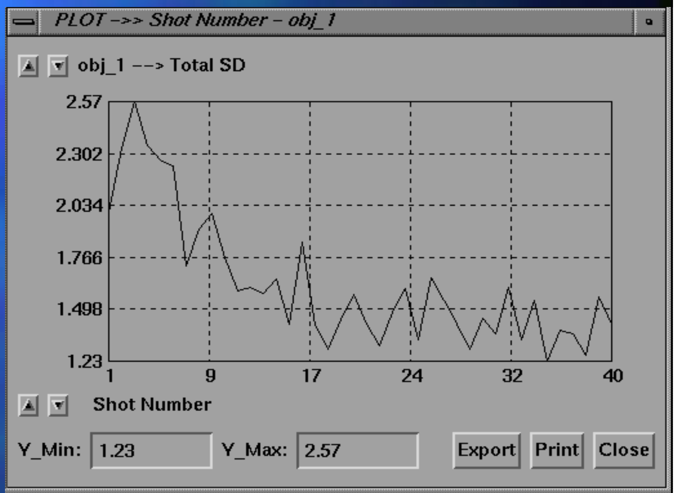
Thermal test correlation (cont.)

- CORRELATION EXERCISE IMPOSING OBJECTIVES





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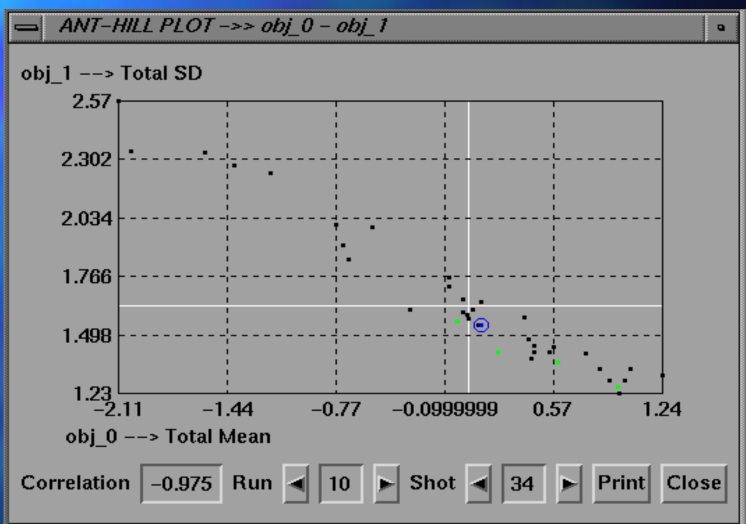
Thermal test correlation (cont.)

- IS IT POSSIBLE TO REACH ALL OBJECTIVES?

It is not possible to reach a mean deviation cero and standard deviation cero

That is the effect of non used input variables



STOCHASTIC APPROACH TO SPACECRAFT TCS

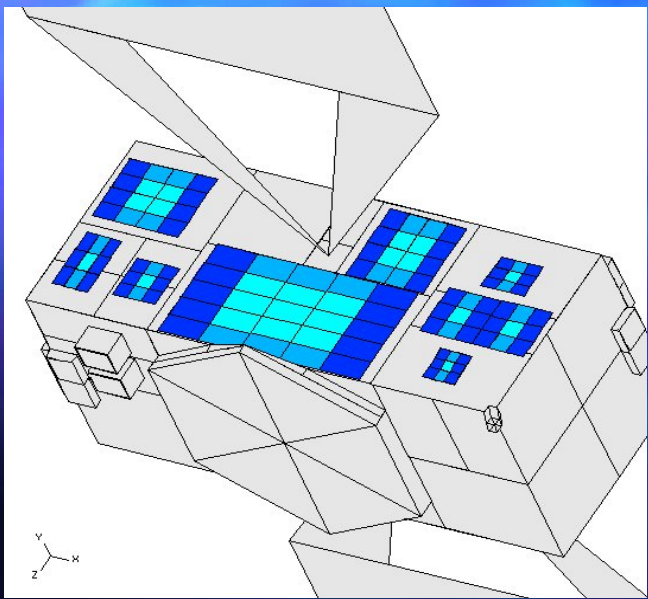
FLIGHT RESULTS CORRELATION. PHASE E

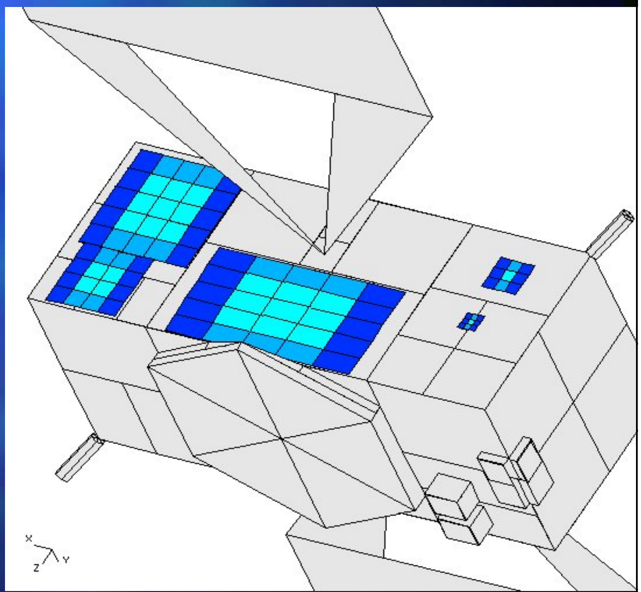
- OBJECTIVES
  - To verify in-orbit performances
  - To justify anomalies and deviations
- PROBLEMS IN THIS PHASE
  - Correlation between model and telemetry data with uncertain enviromental conditions
  - Limited data from S/C to assess anomalies and deviations
- PROPOSAL
  - Stochastic analysis combining all parameters and statistical treatment.
    - Great amount of scenarios to be evaluated
    - Pathologic behaviors
    - Levels of confidence to support conclusions
    - Corrective actions

STOCHASTIC APPROACH TO SPACECRAFT TCS

DESIGN IMPOSING OBJECTIVES

- RADIATORS SIZE AND LOCATION DEFINITION





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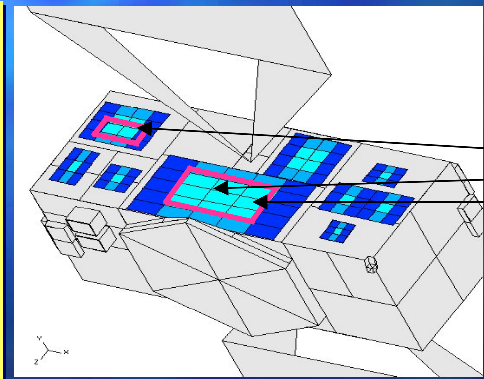
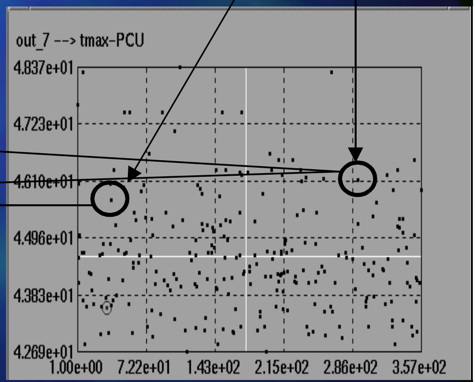
NOMINAL DESIGN AND DESIGN LIMITS. PHASE A

- APPLICATION
  - The design is a input variable.
  - The range of data is larger than the nominal ones.

PCU	32,2W	37,4 W
RWLS	11,3W	11,7W
GYRO E	30,3W	37,8W
OBDH	47,0W	44,5W
Exper 1	58,9W	60,2W
Camera	21.2W	19,5W

PCU	35W±20%
RWLS	13W±30%
GYRO E	35W±20%
OBDH	45W±15%
Exper 1	60W±20%
Camera	18W±40%





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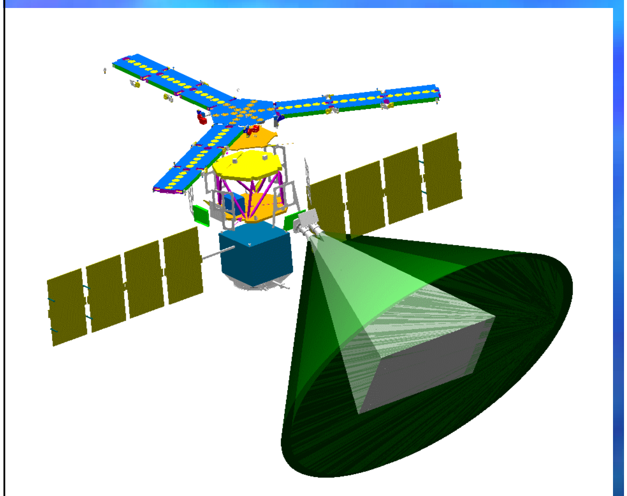
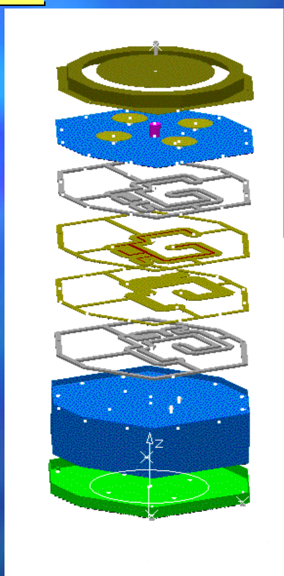
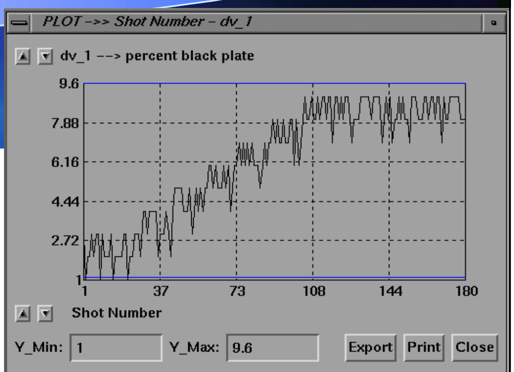
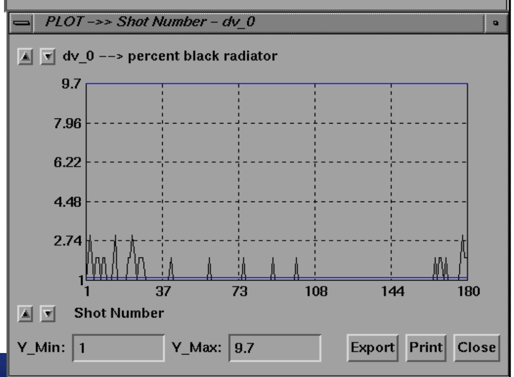
DESIGN IMPOSING OBJECTIVES

- COATINGS SELECTION









- PATTERN between black coating and aluminium. Tmax<50ºC

STOCHASTIC APPROACH TO SPACECRAFT TCS

CONCLUSIONS

- Utilization of probabilistic analysis methods directly considering the scatter of parameters and their distributions (e.g. loads, geometry, and material properties) provides additional information of the designs.
- Introduction of concepts such as Robustness, Flexible, Optimum or Cost Effective allows choosing the "BEST DESIGN"
- Drawbacks: The use of massive analysis requests a very well conditioned heat transfer phenomena of the S/C. This method does not substitute expertise by number of uncontrolled runs.
- Implementation at EADS CASA Espacio:
  - Soil Moisture and Ocean Salinity (SMOS) instrument, (phase A).
  - XMM Mirror Support Platform and Meteosat Second Generation thermal test correlation.
  - Spanish Minisat flight performance verification.
  - NEXT: GalileoSat, A5 Vehicle Equipment Bay