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AEROCAPTURE GUIDANCE ALGORITHM COMPARISON CAMPAIGN

Stéphane ROUSSEAU†, Etienne PEROT‡
Centre National d'Etudes Spatiales
Toulouse, France

Claude Graves, James P. Masciarelli*
NASA Johnson Space Center
Houston, TX
And

Eric Queen*
NASA Langley Center
Hampton, VI

Abstract

The aerocapture is a promising technique for the future human interplanetary missions. The Mars Sample Return was initially based on an insertion by aerocapture. A CNES orbiter Mars Premier was developed to demonstrate this concept. Mainly due to budget constraints, the aerocapture was cancelled for the French orbiter. A lot of studies were achieved during the three last years to develop and test different guidance algorithms (APC, EC, TPC, NPC). This work was shared between CNES and NASA, with a fruitful joint working group. To finish this study an evaluation campaign has been performed to test the different algorithms. The objective was to assess the robustness, accuracy, capability to limit the load, and the complexity of each algorithm. A simulation campaign has been specified and performed by CNES, with a similar activity on the NASA side to confirm the CNES results. This evaluation has demonstrated that the numerical guidance principal is not competitive compared to the analytical concepts. All the other algorithms are well adapted to guaranty the success of the aerocapture. The TPC appears to be the more robust, the APC the more accurate, and the EC appears to be a good compromise.

Nomenclature

AFE	Aeroassist Flight Experiment
APC	Analytic Predictor Corrector
CNES	Centre National d'Etudes Spatiales
EC	Energy Controller
EMCD	European Martian Climate Database
Hap	Apoapsis Altitude
JSC	Johnson Space Center
Mars GRAM	Mars Global Reference Atmosphere Model
MSRO	Mars Sample Return Orbiter
NASA	National Aeronautics and Space Administration
NPC	Numerical predictor Corrector
TPC	Terminal Point Controller

Introduction

The planetary low coast insertion is an important challenge of the current and future interplanetary missions.

† Engineer, Mission Analysis Department
‡ Engineer, COFRAMI, Toulouse, France
* Engineer, Aeroscience and Flight Mechanics Division, Member AIAA

The aerocapture was retained as a competitive candidate for the future Martian mission Mars Sample Return. This collaborative NASA-CNES mission will be preceded by a French demonstrator MARS PREMIER, launched in 2007. Mainly due to budget reason, MARS PREMIER will no more use the aerocapture, but a classical chemical insertion.

In order to demonstrate the aerocapture concept, the CNES has developed four different guidance principles:

- the Analytical Predictor Corrector (APC)
- the Numerical Predictor Corrector (NPC)
- the Terminal Point Controller (TPC)
- the Energy Controller (EC)

In order to consolidate the aerocapture concept, a common NASA-CNES working group has been formed. The group has demonstrated the feasibility of the aerocapture and the capability of all the algorithms to achieve the aerocapture. The current paper presents the evaluation campaign meant to test the different algorithms in order to select the best one for the Martian missions.

The objective is to evaluate the algorithms on different topics, in order to determine if one is more adapted to the aerocapture than the others. This paper is divided in four parts :

- the description of the different test cases
- the simulation tools
- the NASA/CNES comparison
- the analysis of the results and the final ranking of the CNES algorithms.

Test case description

The objective was to evaluate four main criteria :

- The accuracy : being given a set of expected aerodynamic, atmospheric and OD dispersions, the accuracy of the algorithm was defined as the final orbit statistical maximal distance to the targeted orbit.
- The robustness : the robustness was defined as the capability of the algorithm to handle with high dispersions.
- The loads control : the loads corresponds to the thermo-mechanical loads applied to the vehicle during the aerocapture. The loads control was defined as the capability of the algorithm to limit the loads variation, being given a set of expected aerodynamic, atmospheric and OD dispersions
- The complexity : the complexity corresponds to the on-board code complexity. It mainly contains the number of operations, test, loops, and so on.

In order to define test cases, it is necessary to understand what the main parameters for the aerocapture, and the associated uncertainties are.

Aerocapture main parameters

The aerocapture is a very stringent technique, that depends on several parameters. To study the aerocapture, it is necessary to consider either mean parameters (mission description, entry corridor), but also the excepted uncertainties, till the unexpected uncertainties (stress cases).

Mission description

The aerocapture consists in an atmospheric pass to slow the vehicle, and to reach a specific orbit. It corresponds to a given ΔV realized by the aerodynamic force. Therefore, the main parameters are :

- the ΔV value which is fixed by the arrival velocity and the targeted apoapsis,
- the aerodynamic force which depends on the vehicle characteristics (aerodynamic coefficients),
- the atmosphere (density and wind).

It was decided to test different combinations of those parameters to evaluate the algorithms. But an exhaustive combination was not possible, so a set of potential missions was defined to cover different combinations of those parameters.

mission	Infinite Velocity	L/D, Mass	Hap target	Atmospheric model
2005 cls	3.2	.25, 2200	1400	Clear, dust marsgram
2005 opn	2.9	.25, 2200	1400	Clear, dust marsgram
2007 ref	2.6	.28, 2500	1400	Clear, dust
2007 low	3.2	.28, 2500	4000	Clear, dust

mission	Infinite Velocity	L/D, Mass	Hap target	Atmospheric model
2007 polar	2.6	.28, 2500	500	Clear, dust
2007 dust	2.6	.28, 2500	1400	Clear, dust, dust 2, dust 5

The atmosphere has a major impact on the aerocapture. Therefore it is important to use all the existing models. As a consequence, it was decided to use both the European Atmospheric model (EMCD), based on a global circulation model with two nominal scenarios (called clear and dust), and two extreme scenarios corresponding to dust storm conditions (called dust 2, dust 5), and the MARSGRAM V3.8.

This set of missions was considered sufficient enough to cover the different combinations of the main parameters. The '05 missions correspond to high arrival velocity, with low L/D and use of both MARSGRAM and EMCD atmospheric models. The '07 missions cover different altitude targeting and different atmospheric scenarios, with a specific dust storm condition, and a higher L/D.

Entry corridor

Whatever the mission is, the aerocapture is driven by the entry conditions, this is a key parameter. The specific parameter associated to the entry condition is the Flight Path Angle, and the range of acceptable FPA is called entry corridor.

The theoretical aerocapture corridor is the entry FPA range that allows the vehicle to reach the targeted apoapsis at the atmosphere exit.

If the vehicle enters the atmosphere at the steep boundary of the corridor, the vehicle will have to flight "full lift-up" along the whole trajectory in order to reach the targeted apoapsis. On the contrary, if it enters the atmosphere at the shallow boundary of the corridor, the vehicle will have to flight "full lift-down" along the whole trajectory in order to reach the targeted apoapsis. Inside the corridor, it is always possible to find at least one bank angle law that guides the vehicle to the targeted apoapsis. On the outside of the corridor, there is no possibility for the vehicle to reach the targeted apoapsis : the final apoapsis will be lower or higher than the desired value depending on which side of the corridor (steep or shallow entry trajectory) is considered.

This theoretical corridor depends on the atmosphere characteristics, on the ballistic coefficient SC_D/m and on the Lift-to-Drag ratio L/D of the vehicle, on the arrival velocity and on the targeted apoapsis.

- the lower the Lift-to-Drag ratio, the narrower the corridor,
- the higher the arrival velocity, the larger the corridor,
- the lower the targeted apoapsis altitude, the larger the corridor,
- the denser the atmosphere or the higher the ballistic coefficient, the shallower the corridor mean FPA.

Figure 1 presents the sensitivity of the steep and shallow boundaries with respect to the targeted apoapsis altitude considering MARS PREMIER 2007 open window arrival conditions (earliest arrival time, i.e. July 19th, 2008) and a AFE-like entry vehicle with L/D=0.274 and SC_D/m=5.79 10^{-3} m^2/kg (0° trim AoA and 2500 kg mass).

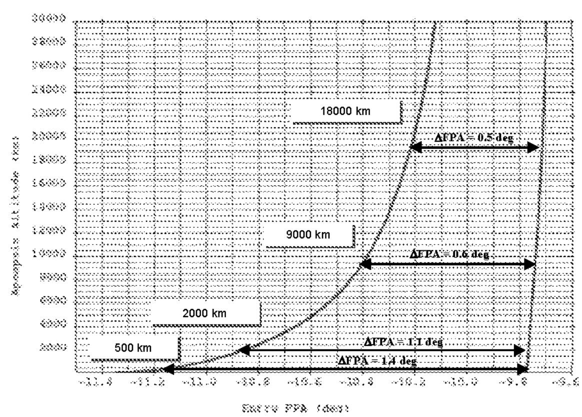


Figure 1 : Theoretical corridor as a function of the targeted apoapsis altitude

A parametric study on the entry FPA, called captured corridor, has been performed on each mission, with all the algorithms to determine the corridor associated to each algorithm.

Expected uncertainties

The aerocapture success depends on the knowledge of a great amount of parameters. The more important are the entry conditions, the aerodynamics characteristics, the atmospheric density, and the on-board navigation. To take into account the uncertainties associated to these parameters, Monte Carlo simulations have been performed with the following dispersions.

	Distribution Type	3-σ or min/max
Mission Uncertainty		
Initial inertial FPA, deg	Normal	0.4
Aerodynamic Uncertainty		
Trim Angle of Attack Incr, deg	Uniform	2.0
Axial Force Coeff Increment	Uniform	10 %
Normal Force Coeff Increment	Correlated	
Atmospheric Uncertainty		
Initial Seed Value	Uniform	
Control System Uncertainty		
Bank Acceleration, deg/sec^2	Uniform	10%

Table 1 Expected uncertainties

Other parameters have been also dispersed like the orbiter mass, the IMU characteristics, …

Stress cases

To characterize the robustness of an algorithm, it is also necessary to consider high uncertainties or off nominal configurations. This is the aim of the stress case analysis. Four topics were retained :

- aerodynamic uncertainties
- thruster failure
- processor failure
- on-board vertical velocity estimation error

Large aerodynamic uncertainties

The vehicle aerodynamic characteristics directly affect the aerocapture performance. The nominal uncertainties taken into account for Monte Carlo simulations were:

- ±2 degrees on the trim angle of attack
- ±10% correlated on the aerodynamic coefficients

These values were doubled for the stress case analysis.

Thruster failure stress cases

The piloting authority is also a major contributor to the aerocapture performance. The nominal uncertainties taken into account for Monte Carlo simulations were:

- ±10% on bank acceleration

To take into account the possible loss of one thruster or more, the following variations were considered:

- -25% and -50% on bank acceleration

Processor failure stress cases

The aerocapture phase is achieved in a fully autonomous way. Once this sequence has been initiated, there is no possibility to abort it. That is the reason why the two on-board processors are in hot or warm redundancy. In case of failure, the time required to swap from the main processor to the backup must not exceed 0.5 to 1 second.

To evaluate the impact of a processor failure and the consecutive computer swap, a sensitivity study to failure occurrence and duration was carried out.

Initial error in the estimated altitude rate

During the aerocapture the vehicle is fully autonomous. The vehicle position, its velocity and its attitude are determined on-board by a strapped down navigation system, initializing few hours before reentry (Orbit Determination) and using IMU sensed accelerations and rotations. The onboard navigated state is not exact and OD error in the initial state cannot be calibrated. It is important to determine the sensitivity of the algorithms to this particular error, especially since guidance accuracy relies for the most part on the altitude rate feedback. So a sensitivity study to the initial altitude rate error was carried out.

Cases definitions

For each mission, we have defined a set of simulations to cover the different aspects :

- corridor analysis
- Monte Carlo simulation
- stress cases

An additional complexity analysis has been done for each algorithm to evaluate the difficulty to implement it.

SIMULATION TOOLS

Aerocapture Simulator

3-DOF and 6-DOF flight simulations have been developed at CNES for Mars aerocapture phase studies as well as for testing, evaluation and analysis of candidate guidance algorithms for the PREMIER 2007 Orbiter.

These simulations include Guidance, on-Board Navigation and Control functions. The 3-DOF flight simulation principle is presented on Figure 2 :

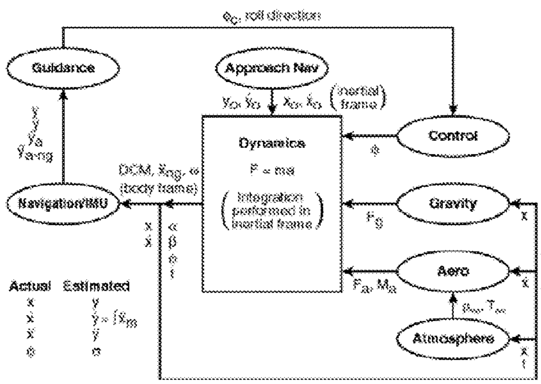


Figure 2 : 3-DOF Aerocapture simulation

The NASA-LaRC 3DOF/6DOF simulation software is based on simulations developed for the Mars 2001 aerocapture and entry studies, as well as Mars Pathfinder and Mars Polar Lander. (Note the Mars 2001 Orbiter mission has been modified to use aerobraking and not aerocapture.) The CNES simulation software was derived from the Atmospheric Re-entry Demonstrator trajectory software that was developed from earlier Hermes project studies.

A cross check of the CNES and NASA 3-DOF trajectory simulator software has been performed. The set of tests includes environment modeling (gravitational field, atmosphere, mars characteristics), aerodynamic characteristics (use of the aerodynamic database derived from the AFE), the piloting function, and the computation of the trim angle of attack. The comparison leads to very similar results on both simulators (less than 200 m on the exit conditions at the end of a guided trajectory). Test cases including guidance, control and navigation functions were jointly defined and performed independently on each simulation. Except for tests including the navigation function that are not yet completed, all the cross-tests give very good results.

CNES/NASA comparison

The following results have been obtain with the CNES simulator (SIMBAD), and the CNES version of the algorithms. A comparison campaign has been performed by NASA to evaluate the NASA version of two algorithms (APC, TPC), for some missions, with the NASA simulator (POST), and the Marsgram model Version 2001. The result are very similar.

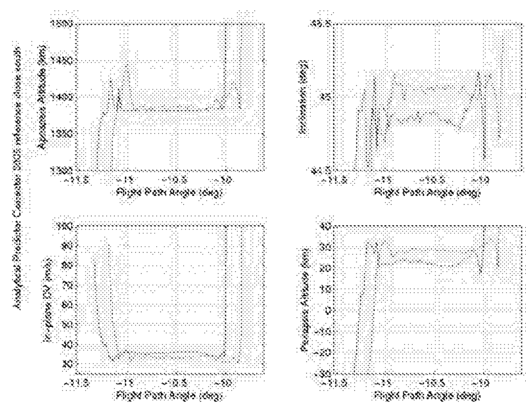


Figure 3 CNES APC corridor analysis

	Min	Max	Width
Theoretical corridor (deg)	-11.18	-9.98	1.20
Captured corridor (deg)	-11.16	-10.01	1.15
Performance (%)	96.0		

Table 2 APC captured corridor

NASA APC

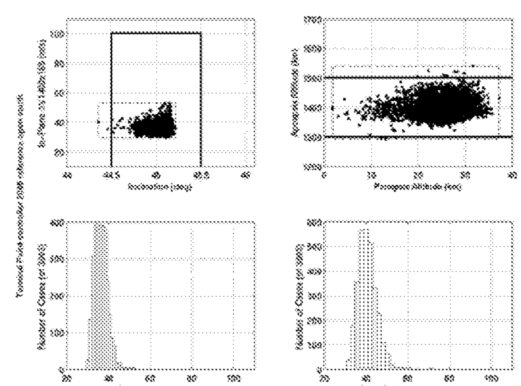


Figure 4 CNES TPC Monte Carlo simulation

Result Analysis

Grading Method

The assessment campaign provided a lot of parameters, like apoapsis altitude, captured corridor, number of elementary operations, …

Obviously these parameters are not comparable, therefore it is necessary to establish a grading method.

The selected grading method consists in giving the best grade to the best algorithm (20, for example, to copy French scholar grading), and fixing an a priori performance corresponding to the worst case (performance associated to the grade 0). Each algorithm is then given a grade defined by the following relation :

$$N = 20.\frac{p - p_{worst}}{p_{best} - p_{wosrt}}$$

The grades obtained on different topics can then be mixed in a "Grade Point Average", taking into account the relative importance of the different factors by choosing proper weightings.

Selected Parameter

Performance criteria Definition

The next step consists in selecting the proper performance parameters for each criterion and determining the associated worst performance.

Robustness

Some simulations were performed to evaluate this particular point. The proposed grading is based on the corridor analysis and the stress cases.

Captured Corridor

The corridor approach consists of a sensitivity analysis of the reached apoapsis altitude with respect to the entry FPA.

The corridor analysis is an essential element of the aerocapture characterization. It includes two aspects :

- theoretical corridor
- captured corridor

The selected parameter is the ratio of the captured corridor to the theoretical corridor.

FPA	$N_{corridor} = 0$
$p_{corridor} = \frac{\text{captured corridor}}{\text{theoretical corridor}}$	$p_{corridor} < 80\%$

Stress Cases

To characterize the robustness of an algorithm, it is also necessary to consider high uncertainties or off nominal configurations. This is the aim of the stress cases analysis. Four topics were retained :

- aerodynamic uncertainties
- thruster failure
- processor failure
- on-board vertical velocity estimation error

For all the stress cases, the selected performance parameter is the final apoapsis altitude. Maximal relative error with respect to the targeted apoapsis altitude was selected as the performance parameter (a null value of this parameter meaning low sensitivity).

Hap	$N_{stressaero} = 0$
$P_{stress} = \max(\frac{\text{nominal} - \min}{\text{target}}, \frac{\max - \text{nominal}}{\text{target}})$	$p_{stressaero} > 0.25$

Thruster failure stress cases

The non acceptable performance was fixed to 25%.

$N_{stressthruster} = 0$
$p_{stressthruster} > 0.25$

Processor failure stress cases

The non acceptable performance was fixed to 50% in case of a 0.5 second failure duration and 100% in case of a 1 second failure duration.

0.5 sec failure duration	1 sec failure duration
$N_{stressprocessor} = 0$	$N_{stressprocessor} = 0$
$p_{stressprocessor} > 0.5$	$p_{stressprocessor} > 1$

Initial error in the estimated altitude rate

The non acceptable performance was fixed to 25%.

$N_{stressprocessor} = 0$
$p_{stressprocessor} > 0.25$

Accuracy

Three parameters were considered to assess this criterion

- the final orbit apoapsis altitude
- the final orbit inclination
- the in-plane ΔV (apoapsis error correction and periapsis raise burn)

The two first parameters correspond to the aerocapture objectives.

The third parameter measures the capability of the algorithm to have a final periapsis as high as possible.

The accuracy is obtained by a statistical approach, using different atmospheric models. A 1000 draw Monte-Carlo simulation was performed for each atmospheric model. A statistical analysis was then carried out globally, considering all the models. Two statistical figures are used to characterize the accuracy parameters :

– The mean value which helps to identify a systematic bias of the algorithm orbit targeting,
– The standard deviation σ which is representative of the algorithm orbit targeting sensitivity with respect to the considered dispersions.

Apoapsis targeting

Performance parameter calculation method

The apoapsis accuracy index performance parameter is defined as the maximum 3-sigma relative error with respect to the targeted apoapsis.

Hap	$N_{accHap}=0$
$P_{accHap}=\frac{\lvert\text{mean-target}\rvert+3\sigma}{\text{target}}$	$P_{accHap}>0.25$

Inclination targeting

Performance parameter calculation method

The inclination accuracy index performance parameter is defined as the maximum 3-sigma error with respect to the targeted inclination.

I	$N_{accI}=0$
$P_{accI}=\lvert\text{mean-target}\rvert+3\sigma$	$P_{accI}>1$

ΔV performance

Performance parameter calculation method

The ΔV2 index performance parameter is defined as the maximum 3-sigma value.

ΔV2	$N_{accdV2}=0$
$P_{accdV2}=\text{mean}+3\sigma$	$P_{accdV2}>100.$

Loads

The loads corresponds to the thermo-mechanical loads applied to the vehicle during the aerocapture. Three major parameters have been considered :

- g-load
- heat rate
- heat load

Note that a trajectory which tends to minimize g-load or heat rate, leads to an increase of the total heat load.

Performance parameter calculation method

The selected index performance parameter to characterize the load on the vehicle is issued from the 99.7% maximal value encountered during the Monte-Carlo simulations.

loads
$P_{loads}=\max_{99.7\%}$

Null grade

G load

The non acceptable performance was fixed to 3.5 earth g's.

$N_{gload}=0$
$P_{gload}>3.5$

Heat rate

The non acceptable performance was fixed to 500 kW/m^2.

$N_{heatrate}=0$
$P_{heatrate}>500$

Heat load

The non acceptable performance was fixed to 70 MJ/m^2.

$N_{heatload}=0$
$P_{heatload}>70$

Complexity

This complexity analysis is very simple. No specific effort was done on the algorithm implementation to improve this particular aspect. It consists of a FORTRAN 77 code analysis.

Different aspects have been taken into account :

- number of executable lines of code
- number of elementary operations
- number of complex functions
- number of conditional statements
- number of loop statements

A specific program was developed to analyze the algorithm Fortran 77 codes.

Specific grading method

For this criterion, a specific grading method, based on an empirical rule, was established for each index performance parameter.

Number of elementary functions

N=20-Nb_elem_operations/50

Number of complex functions

N=20-Nb_complex_functions/10

Number of test instructions

N=20-Nb_conditional_statements/10

Number of loop

N=20-Nb_loop_statements

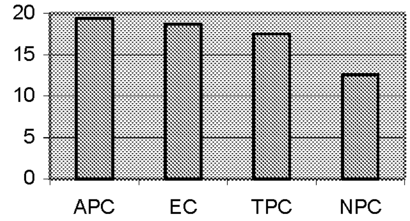
Number of executable lines

N=20-Nb_exec_lines/50

Results

The following results are the final grade obtain for each criteria. They are the result of a complex mix of the different missions, and parameters.

Accuracy



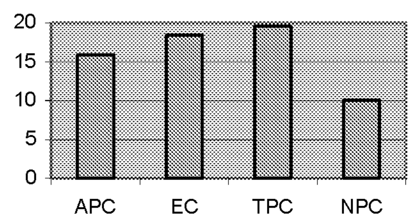
As a preliminary conclusion on the accuracy criterion :

The analytical algorithms (APC,EC) have similar performance with a slight advantage for the APC.

The NPC is too sensitive to on-board navigation errors and its constant bank angle optimization pattern leads to too low periapsis altitudes.

The TPC is a little bit less accurate than the analytical algorithms. However, as soon as navigation errors are taken into account, the gap in accuracy performance is greatly reduced.

Robustness



As a preliminary conclusion on the robustness criterion:

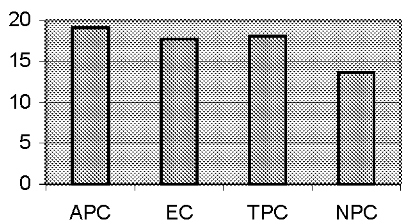
The TPC is the most robust algorithm. It captures almost the whole theoretical corridor for all missions. Its targeting performance is not sensitive to an on-board altitude rate estimation error and quite insensitive to aerodynamic uncertainties and thruster failure.

The EC captured corridor performance and stress cases robustness are good and well balanced.

The APC has a good captured corridor performance. It is sensitive to an on-board altitude rate estimation error. Moreover, the current implemented lateral logic presents a lack of robustness to the thruster failure cases.

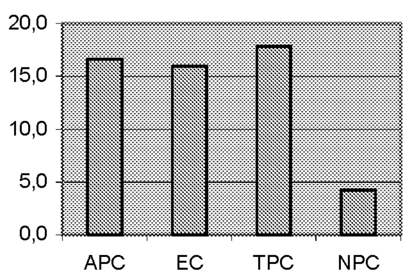
The NPC is less robust to entry FPA variations than the three other algorithms. Furthermore, It is too sensitive to the on-board altitude rate estimation error to be competitive at this stage.

Loads



APC, EC and TPC are well adapted to control the vehicle loads, whereas NPC would require a constrained optimization scheme to control the loads.

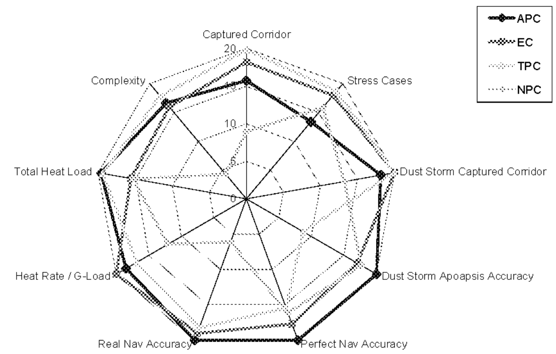
Complexity



TPC implementation (on-board code development and testing) is the less expensive. APC and EC are competitive, their implementation being also very simple. NPC complexity remains too important to be selected as a viable candidate for a first aerocapture mission.

Final Ranking

The following chart gives the detailed profile of each algorithm and presents the ranking for each particular characteristic : corridor, stress cases, dust storm accuracy and robustness, perfect and real navigation accuracy, loads and complexity.



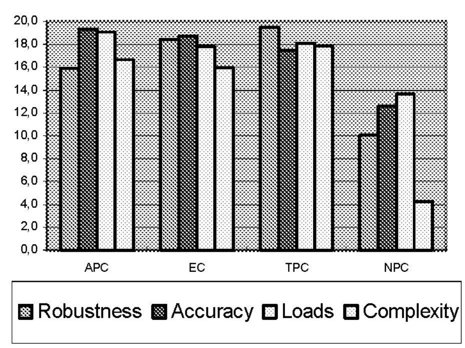
Comments on the chart :

NPC implementation is far more complex than the others. Furthermore, this higher complexity does not provide better robustness, accuracy or load control.

TPC is a very simple and robust algorithm. The current version does not include an on-board estimation of the density scale height. This explains the very poor accuracy of the algorithm for the Dust Storm mission.

APC has been tuned to be very accurate, but it is less robust than TPC and EC, especially for the stress cases. Some additional work is needed to solve the thruster failure sensitivity by modifying the lateral logic.

EC has well balanced performance. Some additional work to fine tune the algorithm should be done in order to improve the heat load control while keeping acceptable g-load / heat rate levels.



This campaign permitted to compare the four guidance algorithms which have been implemented at CNES:

- the Analytical Predictor-Corrector (APC)
- the Energy Controller (EC)
- the Terminal Point Controller (TPC)
- the Numerical Predictor-Corrector (NPC)

This campaign was exhaustive enough to assess the algorithm performance according to the following four relevant criteria :

- robustness
- accuracy
- load control
- complexity

The results were presented on the 30th, 31st of January during a joint CNES-NASA review. The methodology for the performance assessment as well as for the grading of the different algorithms was accepted and final rankings were established according to the different scenarios (different set of weightings).

The conclusions which can be drawn are the following :

Whatever the weightings are, NPC is far from being competitive. Improvement of the algorithm would imply an increase of the complexity, without guaranteeing better performance compared to the other algorithms.

Whatever the weightings, TPC is ranked first. Its performance are excellent except for the Dust Storm scenario. The use of this algorithm is highly recommended, but special effort has to be done to implement a density scale height on-board estimator.

The analytical APC and EC are excellent alternatives to TPC. They are very closed both conceptually and in terms of performance, with a slight robustness advantage for EC and a slight accuracy advantage for APC.

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