THE DESIGN OF AN APPLICATION USED FOR AIRCRAFT STABILITY EVALUATION

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ABSTRACT

One of the most important characteristics of an aircraft is its capability to return to its stable trimmed flight state after the occurrence of a disturbance or gust without the pilot intervention. The evaluation of such behavior, known as the aircraft stability, is divided into three sections: Lateral; Directional; and Longitudinal stabilities. The determination of the stability of an experimental aircraft requires the execution of a Flight Test Campaign (FTC). For the stability FTC the test bed should be equipped with a complete Flight Test Instrumentation (FTI) System which is typically composed by: a Pulse Code Modulation (PCM) Data Acquisition System (DAS); A sensor set; An airborne transmitter; and A data recorder. In the real-time operations, live data received over the Telemetry Link, that are processed, distributed and displayed at the Ground Telemetry System (GTS) enhances the FTC safety level and efficiency. The due to the lack of reliability, recorded data is retrieved in the post mission operations to allow the execution of data reduction analysis. This process is time consuming because recorded data has to be downloaded, converted to Engineering Units (EU), sliced, filtered and processed. The reason for the usage of this less efficient process relies in the fact that the real-time Telemetry data is less reliable as compared to recorded data (i.e. noisier). The upcoming iNET technology could provide a very reliable Telemetry Link. Therefore the data reduction analysis can be executed with live telemetry data in quasi-real time after the receipt of all valid tests points. In this sense the Brazilian Flight Test Group (GEEV) along with EMBRAER and with the support of Financiadora de Estudos e Projetos (FINEP) started the development of several applications. This paper presents the design of a tool used in the Longitudinal Static Stability Flight Tests Campaign. The application receives the Telemetry data over either a TCP/IP or a SCRAMnet Network, performs data analysis and test point validation in real time and when all points are gathered it performs the data reduction analysis and automatically creates Hyper Terminal Markup Language (HTML) formatted tests reports. The tool evaluation was executed with the instruction flights for the 2009 Brazilian Flight Test School (CEV). The result shows an efficiency gain for the overall FTC.

KEY WORDS
Flight Tests, Longitudinal Stability, Telemetry, Decision Aid Tool.

INTRODUCTION

Stability of an airplane refers to its movement or tendency in returning to a given state of equilibrium. More specifically:

- Static stability is defined as its tendency to develop forces and moments that oppose disturbances (e.g. Wind gusts) from a steady-state flight condition [1]; and
- Dynamic stability encompasses the unsteady behavior of an airplane responding to time-dependent aerodynamic forces and moments produced by the aircraft movement.

The better aircraft stability characteristics results in a more controllable platform and therefore it reduces the pilot workload. If a given aircraft is statically stable it will not necessary be dynamically stable. However if the airplane is dynamically unstable it will also be statically unstable.

The aircraft stability characteristics are directly related to its Flight Control System (FCS) behavior. There are two classes of FCS:

- Reversible FCS, where any movement of the cockpit controls results in movement of the aerodynamic surface controls through a direct mechanical linkage; and
- Irreversible FCS, where any movement of the cockpit controls results in movement of the aerodynamic surface controls either partially or completely with the help of an actuation device (e.g. Electro-mechanical actuation device).

The design of aircrafts with reversible FCS should guarantee its full controllability status over the entire flight envelope and in all possible flight regimens [2]. In this case a special attention should be paid for the takeoff and landing procedures, where the aircraft maneuvering should be executed very accurately.

The design and the implementation of irreversible FCS (e.g. Fly-by-wire) should use control laws that guarantees a satisfactory apparent stability for the pilot. It should be noticed that several combat aircraft are unstable. In this case the apparent stability provided to the pilot is obtained by the algorithm of the FCS computer.

The airworthiness regulations such as FAR 25.231 [3] determine the required stability degree for a given aircraft. However the test Pilot will always have the final call for the evaluation of the control workload during the execution of a mission in an experimental aircraft.

Considering that the aircraft flight is symmetrical and in a permanent regimen, the full flight equations could be simplified and the aircraft longitudinal motion (i.e. x-z plane) is uncoupled from the lateral-directional movement [4]. Therefore the aircraft stability and control issues can be analyzed independently.

To evaluate which forces, moments and disturbances that affect the static stability it was considered that:

- Velocity disturbances (u, v and w) are opposed only by forces;
- Angular velocity (p, q and r) disturbances are opposed only by moments; and

- Angle-of-attach ($\propto$) and sideslip (β) disturbances are opposed by moments.

The object of this paper is the design and the evaluation of a novel quasi real-time data processing tool that will be used for the static longitudinal stability flight test campaign.

STATIC LONGITUDINAL STABILITY EVALUATION CRITERIA

When the aircraft is flying in a steady state condition the sum of the longitudinal aerodynamic forces and moments are equal to zero [4]. Therefore:

$$\begin{aligned} F_{A_x} + F_{T_x} - W.\cos(\theta) = 0 \\ F_{A_z} + F_{T_z} + W.\sin(\theta) = 0 \\ M_A + M_T = 0 \end{aligned} \qquad \text{Eq. 1}$$

Where:

- F_{A_x}, F_{A_z} are respectively the x and z axis components of the aircraft aerodynamic forces (lbs);
- F_{T_x}, F_{T_z} are respectively the x and z axis components of the aircraft thrust forces (lbs);
- W is the aircraft weight (lbs);
- θ is the aircraft pitch angle (°);
- M_A is the aerodynamic moment (ft.lbs); and
- M_T is the thrust moment (ft.lbs).

The stability characteristics that should be evaluated include:

- Gusts stability, also known as Angle-of-attach ($\propto$) stability;
- Mechanical characteristics of the FCS; and
- Speed stability and its associated stability terms, that includes:
    - Neutral Point ; and
    - Static Margin.

As example, let's consider that the aircraft that is flying in steady state condition (eq. 1). This airplane is considered to be static stable if it develops a reaction moment (M_r) that opposes the angle-of-attach disturbance caused by wind gusts. Therefore for a stable airplane the following condition applies:

$$M_R = \frac{\partial(M_T + M)}{\partial \propto} < 0 \qquad \text{Eq. 2}$$

At the Flight Test Campaign the determination of the speed stability terms requires the execution of flights in at least two distinctive Center of Gravity (CG) configurations. The recommended choice is the most forward and the most rear CG locations.

The selected longitudinal stability test point starts in a steady flight condition, where the aircraft is trimmed. Then data acquisition occurs at two conditions:

- Deflection stability, also known as stick-fixed stability where it is measured the stick deflection to maintain the target aircraft speed; and

- Force stability, also known as free stick stability where it is measured the stick force required to maintain the target aircraft speed.

At each test point the aircraft is trimmed to fly in a constant speed (V_{Trim}) as required by the test order. Then the Test Pilot executes the following sequence:

- Initially it is determined the mechanical characteristics of the FCS. This includes the evaluation of:
  - The inefficiency range and;
  - The force threshold plus the friction (;
  - The compensation range;
  - Friction force; and
  - The position displacement and the number of oscillations caused by a unit impulse stimulus at the stick.
- Then the TP performs several 10 second speed stabilizations at $V = V_{Trim} \pm 15\%$ or $V = V_{Trim} \pm 50$ Kt which is lower. At each point it should be registered the:
  - Stick displacement ($D_{\delta m}$) versus the aircraft equivalent speed (V_e) plot;
  - Stick force (F_{Dm}) versus the aircraft equivalent speed (V_e) plot; and
  - The exact aircraft x-axis CG location (x_{CG}).

The condition of stick-fixed neutral stability requires determination of the CG position ($P_{CG} = [x_{CG} \quad y_{CG} \quad z_{CG}]$) for which the ratio between the stick position ($D\delta_M$) and the Lift coefficient (C_L) equals to zero. A method of doing this in flight is to fly the airplane at a given CG location with various speeds and to measure the corresponding elevator angle to trim. The procedure is repeated for different CG locations. The slope of the $D\delta_M/C_L$ curve are plotted against x_{CG} and the intersection of this curve with the x_{CG} axis gives the stick fixed neutral point.

For the stick free neutral stability the CG position is obtained when the ratio between the stick force ($F\delta_m$) and the longitudinal angular speed (q) divided by C_L is equal to zero. This flight is executed by flying the airplane with a given CG location at different speeds and measuring the corresponding $F\delta_m$. The procedure is repeated for different CG locations. The slope of the $F\delta_m/\delta C_L$ curve are plotted against x_{CG} and the intersection of this curve with the x_{CG} axis gives the stick free neutral point.

For all test points the acceptance condition are the following:

- For the trimmed condition:
  - $V_e = V_{Trim} \pm 2$ kt;
  - $\propto = 0^\circ \pm 1^\circ$;
  - $\beta = 0^\circ \pm 1^\circ$; and
  - $Z_{pb} = Z_{pb_{Trim}} \pm 100$ ft.
- For each stabilization around V_{Trim}:
  - $V_e = V_{Trim} + \delta V_{Trim} \pm 2$ kt;
  - $\propto = \overline{\propto} \pm 1^\circ$;
  - $\beta = \bar{\beta} \pm 1^\circ$; and
  - $Z_{pb} = \overline{Z_{pb}} \pm 100$ ft; and
  - $Z_{pb} = Z_{pb_{Trim}} \pm 1000$ ft;

REQUIREMENTS FOR A FLIGHT TEST CAMPAIGN

The Flight Test Campaign goal is to safely gather the required information from the Test Bed with the best possible accuracy. To do this it is required to integrate into the test bed a complete Flight Test Instrumentation System (FTI) to acquire, store and transmit test data. Then due to safety reasons real time data is transmitted over the Telemetry Link to the Ground Telemetry System (GTS) which process, store and display real time data for flight safety and test point validation purposes.
In this scenario the GTS works in three phases:

1. Pre-mission, where all setup data is loaded and stored into the GTS Data Base to allow the acquisition and processing of the test data;
2. Real-time, where Telemetry data is acquired, decomutated, stored, processed and displayed. In real time the main goal is to assure the flight safety and to validate all test points; and
3. Post mission, where recorded data is retrieved, processed and sliced according with the executed tests points. With all slices the engineering staff could perform the post mission analysis and write the flight report.

So, this process is not very efficient, because data acquisition, decryption and conversion are performed twice. In real time with telemetry data and in post mission with the recorded data. The usage of this record/reproduce architecture relies on the fact that telemetry data is less reliable as compared to the recorded data, because the real time telemetry link is more susceptible to noise and dropouts.

Considering that the telemetry link reliability can be upgraded with the usage of new technologies (i.e. iNet) [5], in the near future it would be possible to use live data for data analysis and bring the post mission operations to a quasi-real time environment (Figure 1). In this sense, as an experimental development our Research and Development group along with EMBRAER implemented a pilot application to be used for the Static Longitudinal Stability Flight Test Campaign.

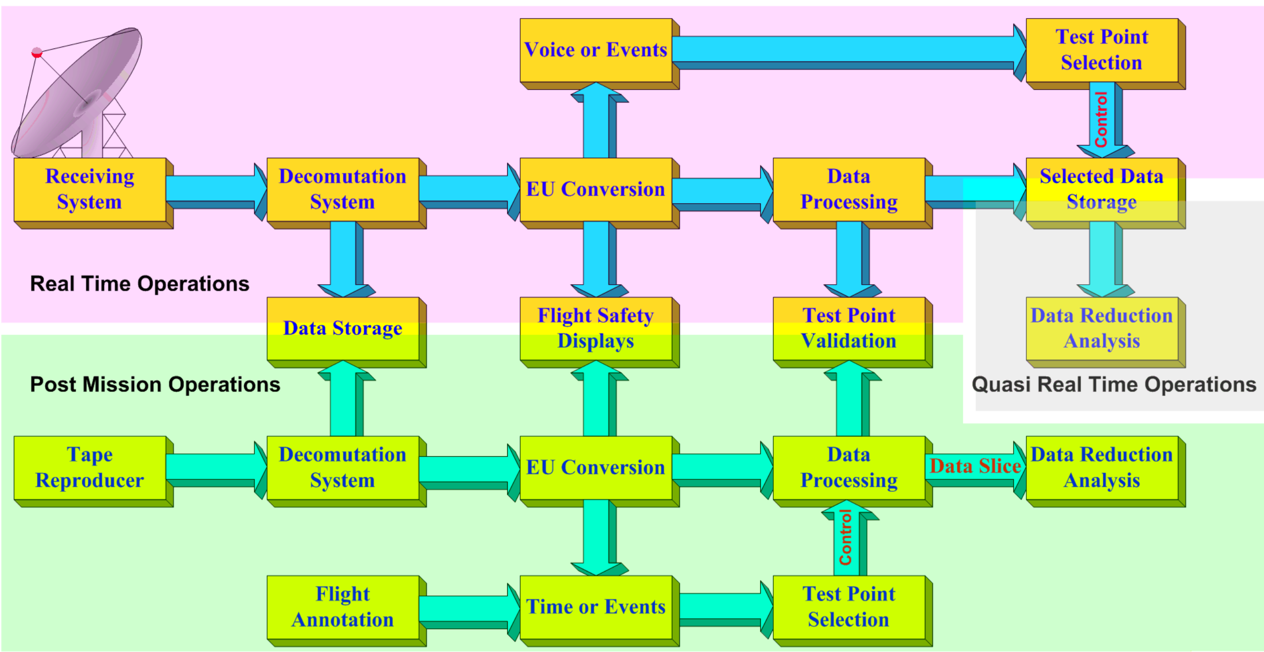

Figure 01 – GTS Operations.

TOOL DEVELOPMENT

The tool integrates a data acquisition application and a data processing application. The data acquisition tool was developed under C sharp using the Microsoft Visual Studio .Net Interface Development Environment (IDE) with calls to Matlab® application. The data processing software is simply a Matlab® Script.

This architecture (Figure 2) allows the creation of customized Matlab® Scripts or Simulink® Real Time Models by the Engineering Group that will be used in Real time for data processing of the flight test campaigns. In particular for this application it was required the implementation of the following capabilities:

1. Real time data acquisition;
2. Real time data validation;
3. Test point data extraction and storage;
4. Post-mission data analysis;
5. Report Generation; and
6. Data storage;

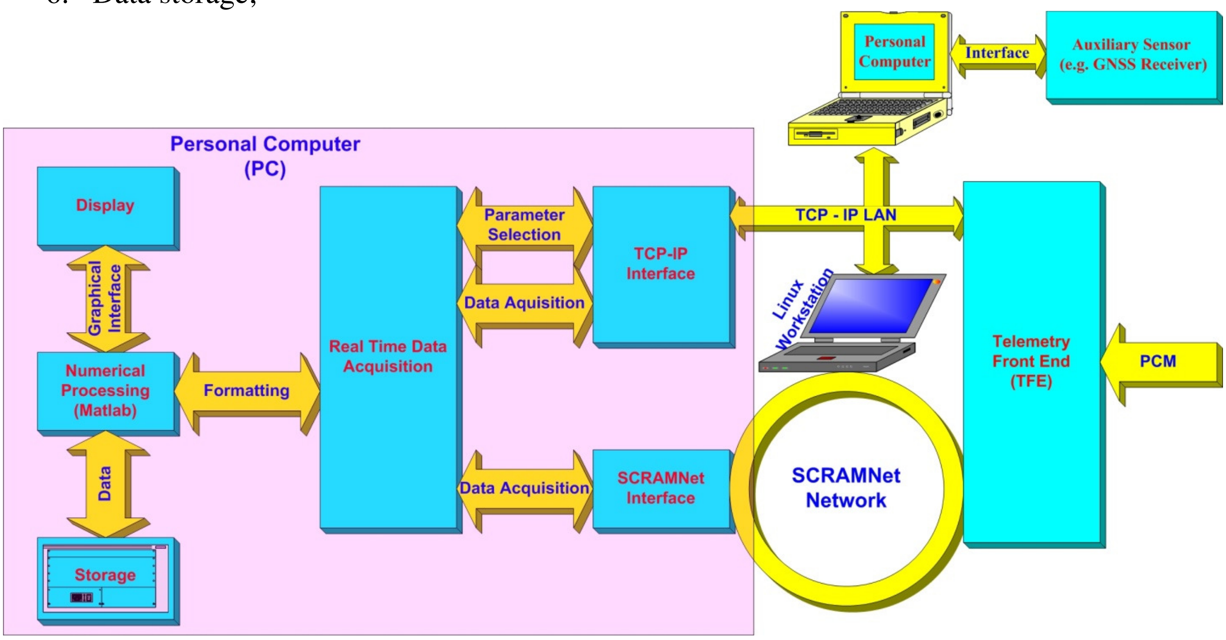

Figure 02 – Data Acquisition / Processing Architecture

The data acquisition application performs the following tasks:

1. It establishes a sockets connection with any GTS data servers (i.e. LINUX Workstation) or any other data source (e.g. GNSS Ground Receiver);
2. It request the current available parameter list that are current being distributed from such data server and presents for user selection;
3. It request the transmission of the chosen dataset over either the TCP-IP or the SCRAMNet networks;
4. It gathers requested data and creates a circular time history buffer for temporary data storage; and

5. When the buffer is filled (buffer size is user selectable) or if time out event occurs (time out period is user selectable) the buffer is appended into a Matlab® workspace for data processing.

The data processing algorithm executes the data analysis in two modes:
1. In real time mode where the acquired data is compared to the validation parameters and displayed at the Computers Monitors of the Ground Telemetry System (GTS) to allow test point validation;
2. In quasi-real time where validated test points are submitted to a post mission data analysis package to produce the required test results. Then the processed data are displayed at the GTS monitor screen. This process allows the Ground crew to visualize the partial test results immediately after the execution of the Test Points.

After the execution of the last valid test point, the operator can store all data for latter reference and the Final Test Report can be generated as a Hyper Text Markup Language (HTML) format.

To allow the setup of the required stabilization condition customized for each planned test point a graphical interface was developed where the user can setup, present, save or retrieve all required setup parameters.

During the real time operations the application continuously plots the aircraft altitude (Z_p), calibrated air speed (V_c), stick force ($F\delta_m$) and stick displacement ($D\delta_m$) along with its validation parameters and flags. Also the application numerically displays the current value of the elevator compensator position (δm_c), the engine RPM (N_G), the total fuel (TOT), the angle-of-attach (α) and the angle of sideslip (β), the pitch (θ) and roll angles (φ), and the aileron position (δ_l).

Then, the main application computes the equivalent speed (V_e), the CG x-axis position (x_{CG}), the Lift coefficient (C_L); and the Basic Dynamic Pressure (q_b). With these parameters the application plots the following partial results:

- The stick force ($F\delta_m$) versus V_e;
- The stick displacement ($D\delta_m$) versus V_e;
- The stick position (σ_m) versus V_e;
- The stick position (σ_m) versus C_L;
- The ratio between $F\delta_m$ and the longitudinal angular speed (q) versus C_L;
- The ratio between $D\delta_m$ and the C_L deviation (δC_L) versus x_{CG}, that gives the stick fixed neutral point for this flight; and
- The ratio between $F\delta_m$ and δC_L versus x_{CG} that gives the stick free neutral point for this flight.

Upon the execution of the last valid test point, the user can save all acquired data, for further reference, and to generate the final test report.

The graphics that composes the final report also include the mechanical characteristics of the FCS that are evaluated after the trim.

TOOL EVALUATION

The tool evaluation was carried out with the Xavante Jet Trainer (XAT-26) manufactured by EMBRAER. The FTI System was composed by an Airborne Pulse code Modulation (PCM) Data Acquisition System (DAS), a PCM Tape Recorder, a GPS/IRIG-B Time Base and a set of Transducers.

FTI measurement accuracy depends mostly on the calibration procedures. Then for all FTI parameters it was determined the error minimization model and the associated uncertainty (Figure 3), as defined by the EA-4/02 Standard [6]. This task was executed by the SALEV system [7] which is fully compliant with the ISO 17025 Standard [8]. SALEV takes into account the errors of all components involved into the data acquisition process (i.e. Full chain). This includes, among others, the sensor, the signal conditioning amplifier and filters, the data acquisition system, and the RAW-to-EU residual errors.

One required information for this campaign is the exact location of $P_{CG} = [x_{CG} \quad y_{CG} \quad z_{CG}]$. Although P_{CG} can be computed for a specific aircraft configuration using its specific weight and balance procedures [9], P_{CG} location changes while the aircraft is flying due mostly to its fuel consumption. In this particular case, the test bed is the EMBRAER XAT-26 jet trainer s/nº FAB 4509. Considering no store separation occurs during the flight, y_{CG} and z_{CG} are constant. Therefore the computation of x_{CG} location requires the aircraft weight and balance data [10]. With such data, it will be estimated the polynomial coefficients of the curve that provides the relationship between the aircraft Total Fuel (TOT) and x_{CG} location (Figure 4), using the least squares techniques. The resulting model for our test bed is:

$$x_{CG} = (2.76145x10^{-8}xTOT^2 \quad -7.54559x10^{-5}xTOT \quad +8,86533) \qquad \text{Eq. 3}$$

Then the tool evaluation was performed in three steps, as follows:

- In the pre-mission operations, where the validation parameters for each planned test point and the ADS calibration coefficients are defined and stored for future access;
- In the real-time operations, where the received Telemetry data is acquired and displayed for test point validation and storage; and
- In the quasi real-time, where the partial and the final test results are displayed. Upon the execution of the last valid test point the user can generate the final test report and to store all gathered data for future access and analysis.

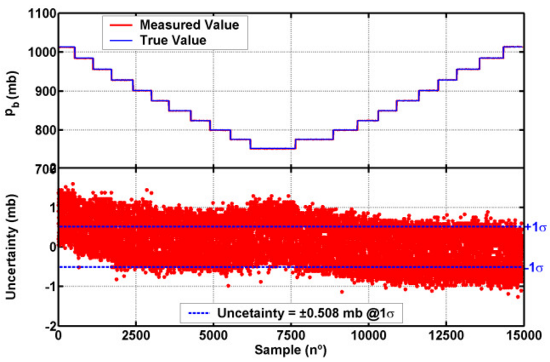

Figure 03 – Static Pressure Calibration Results

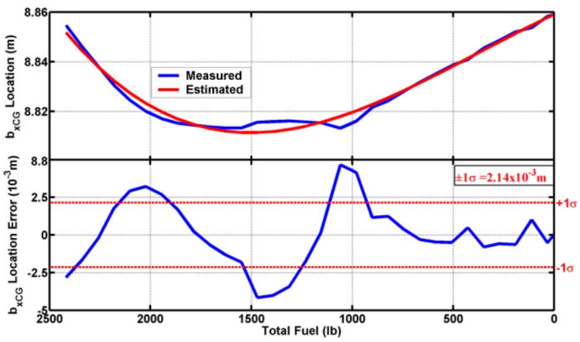

Figure 04 – XAT-26 x_{CG} location model

For the real-time operations the user has to start the data gathering application and then the data processing application that is basically a Matlab® script. At the data gathering application the user:

- Selects the data source, either TCP-IP or the SCRMNet networks;
- Selects the data set to be acquired;
- Controls the data acquisition flow to the Matlab® Workspace; and verifies the data acquisition status; and
- Verifies the data buffering status at the Matlab® Workspace.

Once established a successful data gathering the user should start the data processing application. Initially this program will retrieve the data validation parameters that was previously saved by the user, otherwise those parameters should be manually entered at this time. Upon the completion of this task the application presents its main screen (Figure 10) where the user can:

- Select the current test point and/or manually readjust its associated setup parameters;
- Visualize the FTI real time data along with its acceptance limits to validate the test points;
- Perform mission and data control and visualize current data acquisition status;
- Visualize the preliminary and final (upon the execution of the last valid test point) test results; and
- Generate the final test report and store all gathered data for latter analysis or further reference.

The tool evaluation using live data acquired at the CEV performance FTC presented satisfactory results (Figure 5). Therefore the tool was successfully validated.

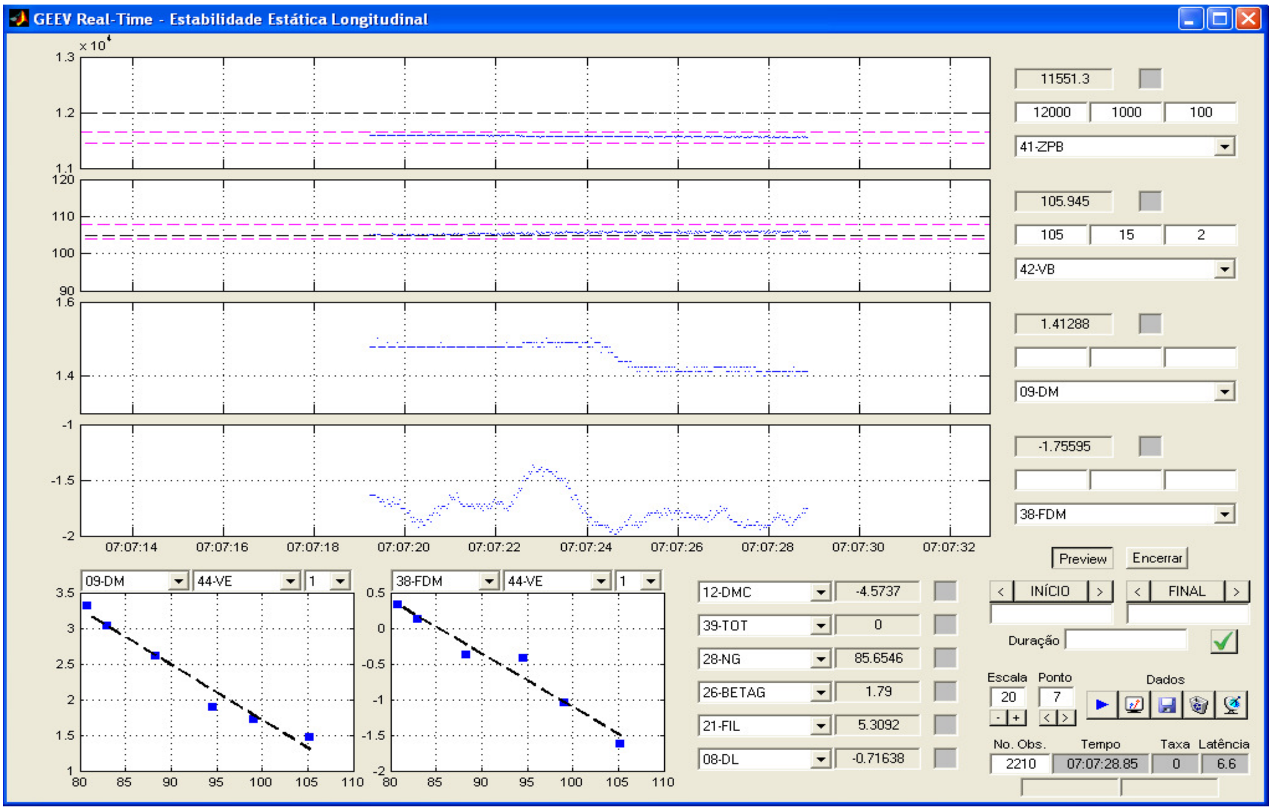

Figure 05 – Flight Test Results

CONCLUSIONS

As presented the development of a real time data processing tool for the Longitudinal Stability Flight Test Campaign was successfully achieved and evaluated.

The major achieved objectives are the capabilities to:

1. Validate all test points in real time;
2. Perform post-mission data analysis at the end of the last valid test point; and
3. Create the flight test report in a quasi-real time.

The next step that will be pursued is the development of a similar tool to be used for performance flight test. In this case, the test range is larger (around 40 Nm), then the Telemetry Link reliability will be jeopardized and this will be the major issue to be addressed.

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