ATMOSPHERIC DRAG MODELLING AND FORECASTING

MISSION ANALYSIS & OPERATIONS

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COMET Space Weather & Orbitography

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CNES

Introduction

2016-2020 summary

Go forward ?

Partial derivatives

1

INTRODUCTION

Introduction

What matters?

- **On LEO orbits, the orbit prediction is unperfect :**
  - all contributions to drag are with uncertainties

$$\gamma = C_f \frac{1}{2} \rho \frac{SC_x}{m} V^2$$

2015 expectations

- **Characterize the orbital prediction errors in MISSION ANALYSIS**
  - Short term : a few hours
  - Mid-term : a few days
  - Long term : N x 10 days
- **Improve the operational process of orbital prediction**
  - Choice of atmospheric model
  - Choice of solar activity inputs
  - Choice of S.Cx model
  - Choice of strategy : how to apply the observed error?

Goal of this presentation?
Share our state of art

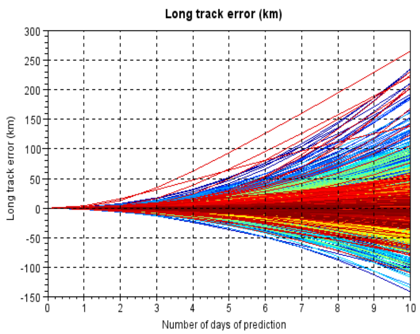
2016 state of art – by examples

Additive method for mission analysis

- **Operational period expected? choice of a past observed period**
  predicted and real flux/indices usage
- **Mean surface and constant Cx**

Cf. CCT ORB 10/04/2014

Using a dedicated tool, we obtain the error due to solar activity uncertainty



Error >0 ? drag under estimated

Reality minus Prediction
⇔ density model with observed actsol
minus density model with predicted actsol

Error <0 ? drag over estimated

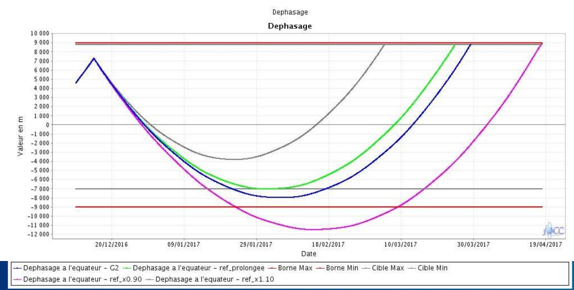
Fine .. But …

- Only absolute error analysis
- Density model not challenged
- Too oversizing ?
- Some observed cases of undersizing …

- **And we added a 20% margin due to observation on Cf**

Operational problematic

- *Unknown future*



Empiric approach

- Limited trust in operational tools …

2016-2020 SUMMARY

MODELS, TOOLS

2016 workplan

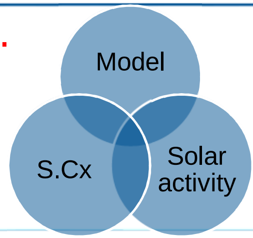
Observe

- Use of available operational data ELISA, SPOT, HELIOS, JASON, GRACE, …
  - Error between prediction and observation, with different models, differents data : F10.7 and F30 (R&T)
  - Operational Cf restituted
  - Relative errors instead of absolute errors
  - S.Cx model tests

Analyze

- Working group

Some lack of time / wrong directions …
4 correlated thematics !



Improve

- Empiric method for mission analysis? The initial driver
- Preconisations for operations? The final purpose
- Monitoring in operations ? The dream
- Go forward? The 2022 status-quo

Thematic#1 : atmospheric model

Several comparisons to « identify » which model « fits the reality »

1. On 3 extrapolation duration (1d, 10d, 30d)

2. With observed solar activities

For : DM2013 F10.7 / DM2013 F30 / MSIS2000 / Jacchia 2008

Bias identified : GS recommandation to check the « meta model » of S.Cx

MSIS2000 allways used in operational tools

But DTM 2013 F30 to target (and SWAMI at mid term)

Thematic#2 : Solar activity forecast

Solar activity measurements

- F10.7 / Canada
- F30 / Japan (continuity?)
- Geomagnetic indices

Solar activity prediction (Solar flux forecast)

- Today: NOAA service for CNES satellites
- CNES R&T : CLS portal ➔ promising

Atmospheric models

- Europe : DTM (use of F30 or F10.7)
- Today: NRLMSISE-00 for operational use with F10.7

Atmospheric drag prediction

- Orbitography: satellite operations
- Orbitography: debris & re-entry
- Mission Analysis

❖ **analyses show better drag predictions with F30 than with F10.7 (through the DTM model)**

❖ **CNES development and investment (R&T) in F30 and F10.7 predictions together with CLS and LPC2E support (CLS: https://spaceweather.cls.fr/services/radioflux/)**

Thematic#3 : S.Cx

Elaboration with Cook formula of « 3D » S.Cx model for a spacecraft (CERES)

- **PERT tool : S.Cx table as a function of altitude and solar activity**
- **PATRIUS tool : Global Drag force interpolating this table at each instant**

Operational use since March 2022

Thematic#4 : mission analysis method (1/2)

Empiric intermediate method

XX_P = *Predicted*
XX_R = *Real and Unknown*
XX_{mod} = Computed with observed flux

$$\gamma = \frac{1}{2}\,\rho\,\frac{S\,C_x}{m}\,V^2$$

Drag error : $\varepsilon_F = \gamma_P - \gamma_R = \left[1 - \frac{(SC_x)_R}{(SC_x)_P}\frac{\rho_R}{\rho_{mod}}\frac{\rho_{mod}}{\rho_P}\right]\gamma_P$

Along track error : $\varepsilon_{LT} \cong \iint_t 3\varepsilon_F dt^2 = \left[1 - \tau_{SC_x}\tau_{mod}\tau_{actsol}\right]\boxed{\iint_t 3\,\gamma_P dt^2}$

LT_p : along track predicted distance

Relative error : $\tau_{total} = \tau_{SC_x}\tau_{mod}\tau_{actsol} = 1 - \frac{\varepsilon_{LT}}{LT_p}$

Model error
⇔
was managed
via the previous 20% margin due to observation on Cf

Solar activity error
⇔
managed
by the 2016 existing tool

Thematic#4 : mission analysis method (2/2)

Previous method was without $\tau_{SC_x}\tau_{mod}\cdots$

$\varepsilon_{LT} = 1{,}2(1-\tau_{actsol})LT_p$

Orbit

$\sigma = f(\bar{F})$

Empiric law

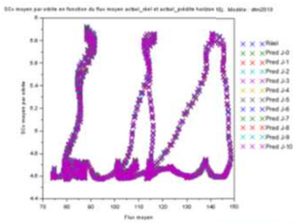
Mean value

$\overline{C_{bal}}$

$C_{bal} = \frac{SC_x}{m}$

2019 improvment

$\overline{Cbal} = g(\bar{F})$



Tool

τ_{actsol}

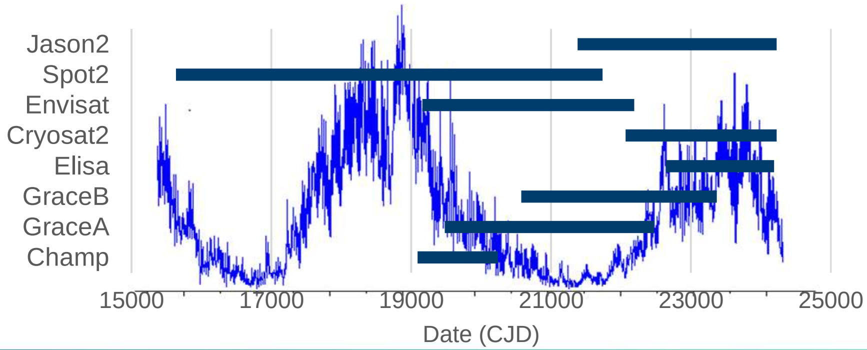
$\sigma_{\tau_{SC_x}\tau_{mod}}$

LT_p

Tirage aléatoire $\mathcal{N}(1, \sigma_{\tau_{SC_x}\tau_{mod}})$

τ_{tot}

$\varepsilon_{LT} = (1-\tau_{tot})LT_p$



GO FORWARD

Need of a new start

Mission analysis point of view

- **The actual empiric method is not perfect, but is our actual reference**

Operational point of view

- **Cf prediction usage workplan?**
- **Partial derivatives approach (see last section)**
- **DTM2013 or SWAMI deployment to anticipate**

Other Ideas

- **With LPC2E/CLS help : F30 forecast consolidation (Europe independance, …)**
- **Prediction of geomagnetic indices**
- **Long term dream? develop « SpaceWeather laboratory »**
  - use the daily CNES data,
  - continue to explore,
  - Machine learning …
- **SWAMI usage**

4

CURRENT AND FUTUR WORKING AXES

The drag acceleration and the sources of uncertainty

We can represent the **drag acceleration** with the following equation:

$$\gamma = C_D * \frac{1}{2}\rho\frac{SC_x}{m}V^2$$

- **Low contribution to uncertainty**:
  - **Velocity**: a few meters per second (spacecraft + atmosphere velocity) of uncertainty relative to several kilometers per second
  - **Mass**: a few grams compared to hundreds of kilograms.
- **High contribution to uncertainty**:
  - $\boldsymbol{SC_x}$: the reference area and the drag coefficient imply complex physics. They mainly depend on the *attitude* of the spacecraft. We can introduce the following notations:

    $$SC_x(Attitude) = \widehat{SC}_x(Attitude) + \varepsilon_{SC_x}(Attitude)$$

    Notations
    X : Real value
    $\hat{X}$: Model value
    ε : Error

  - **Atmospheric density**: implies complex physics of the whole earth system. It has an important dependence to the *solar activity*. We can introduce the following notations:

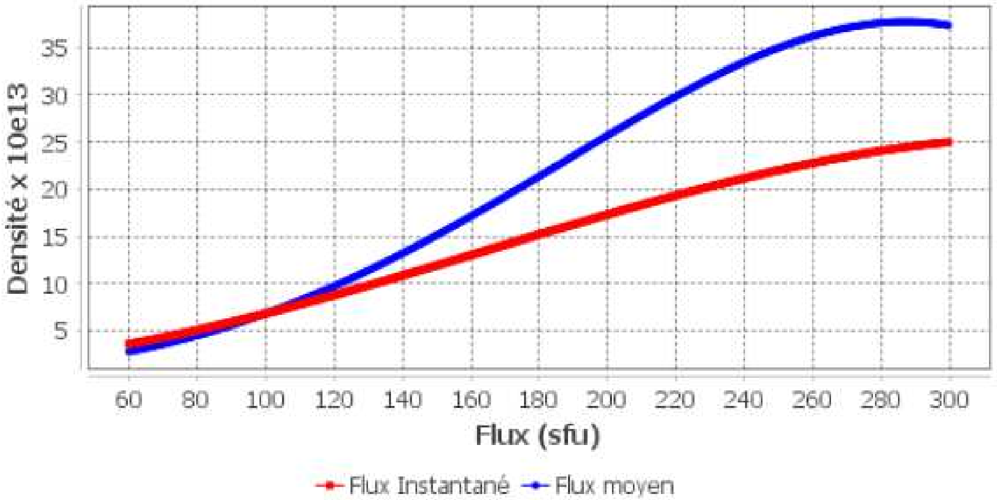
    $$\rho = \hat{\rho}(SolAct) + \epsilon_\rho$$

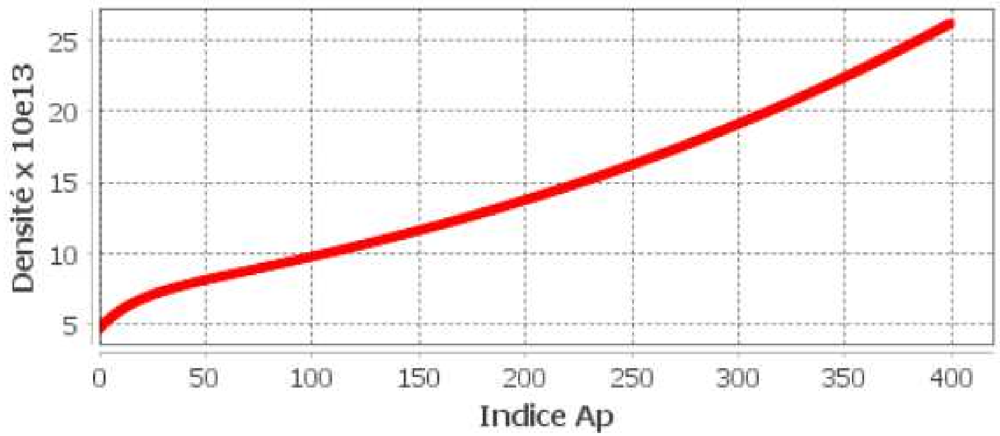
  - $\boldsymbol{C_D}$: adjustment coefficient to fit observations. It *absorbs* all the *lack of modelling* of the previous bullets.

Atmospheric model partial derivatives

The errors of the atmosphere density are the addition of:

Notations
X : Real value
$\hat{X}(t+\Delta t)$: Model value at date $t+\Delta t$
$\varepsilon(t,\Delta t)$: Model error at date $t+\Delta t$, depends on



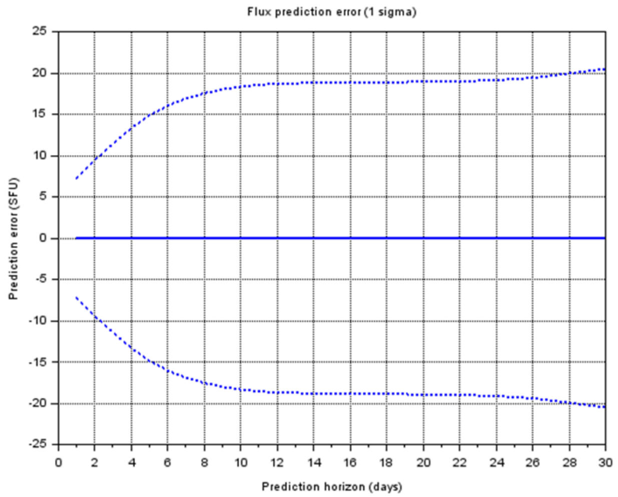


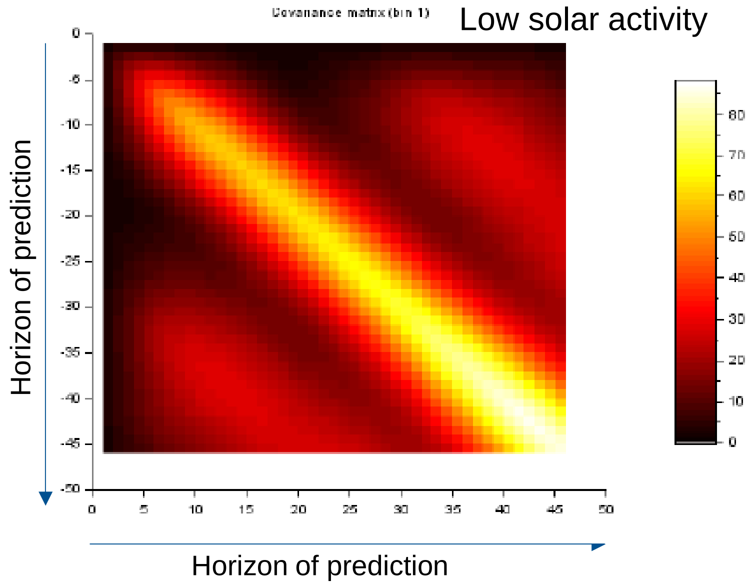
- These partial derivatives of the atmospheric model allow to compute trajectory partial derivatives (through numerical integration):

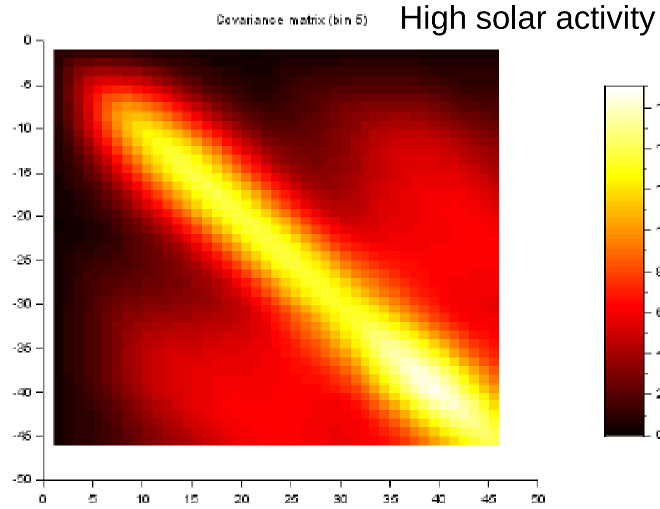
$$dX \approx \frac{\partial X}{\partial Fl} dFl + \frac{\partial X}{\partial Ap} dAp$$

Atmospheric model partial derivatives

- Good knowledge of the solar activity error statistics thanks to a long historic of data
  - Warning: the **temporal correlation** between predictions must be taken into account







- Thus, for a given orbit, we can have a good knowledge of the orbital prediction error statistics due to the solar activity prediction errors

- How to use this info?
  - To better understand the contribution of each post of error
  - For mission analysis: Take into account a better coupling between orbit determination errors and orbit prediction errors
  - For covariance propagation
  - Difficulty: How to integrate the other drag acceleration post of errors to have a full error budget ?

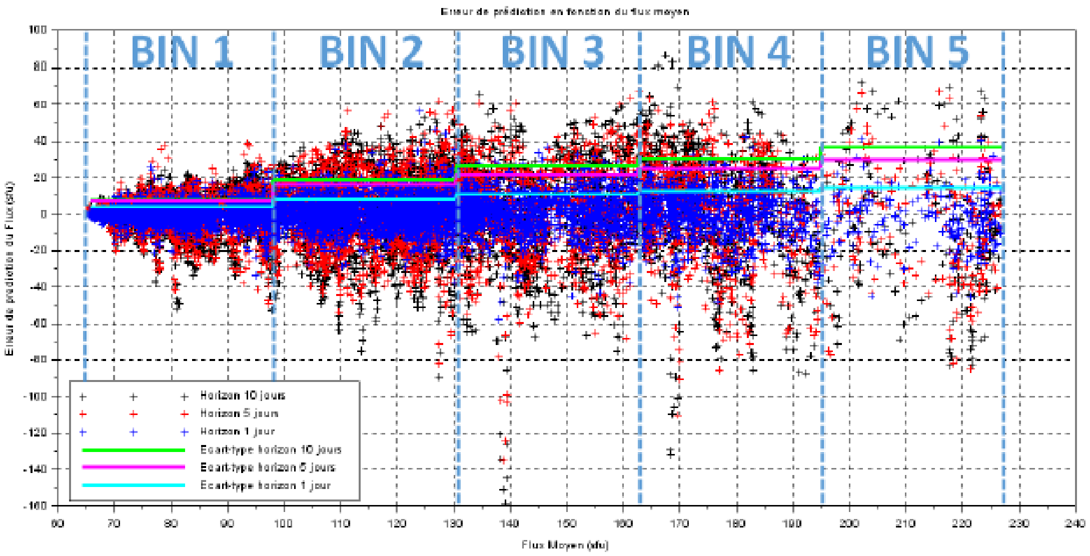
Futur work

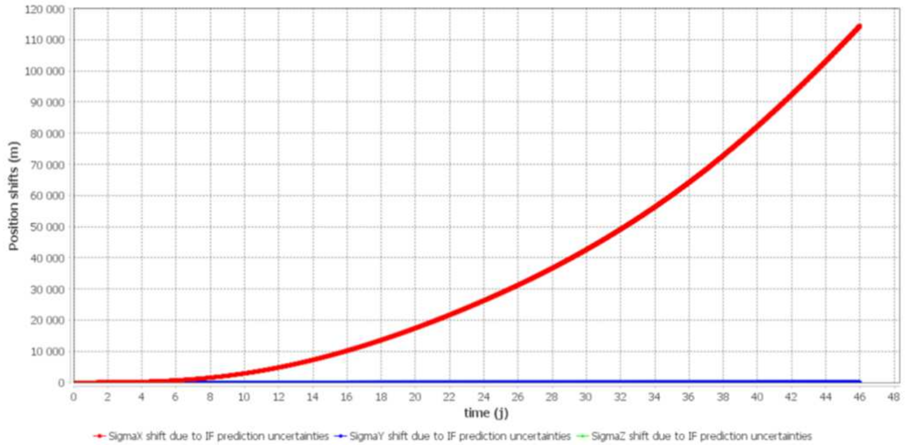
- Include the draft of the partial derivatives computation in our softwares

- Define a protocol to use it in operations for covariance prediction (collision risk management)

- Work on the best way to use the Cd estimation for the orbit predictions

Annex: orbit error from solar activity prediction errors





Bin représenté	1	2	3	4	5
Ecart-type de la dérive (en km)	1,6	9,5	37	90	114

After 45 days of prediction