Medium-term predictions of F10.7 and F30 cm solar radio flux with the adaptive Kalman filter

1-24 months ahead

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RESONANCE

Radio **E**missions from the **S**un: **ON**line **AN**alytical **C**omputer-aided **E**stimator

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Relevance

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F10.7 and **F30 cm** radio flux **are required** by most models characterizing the state of the upper Earth's atmosphere, such as the thermosphere and ionosphere in order to specify **satellite orbits**, **re-entry services, collision avoidance maneuvers** and modeling of **space debris evolution**.

Atmosphere models in use:
NRLMSIS-00, DTM-2013, GOST-2004
Bastida Virgili, 2017

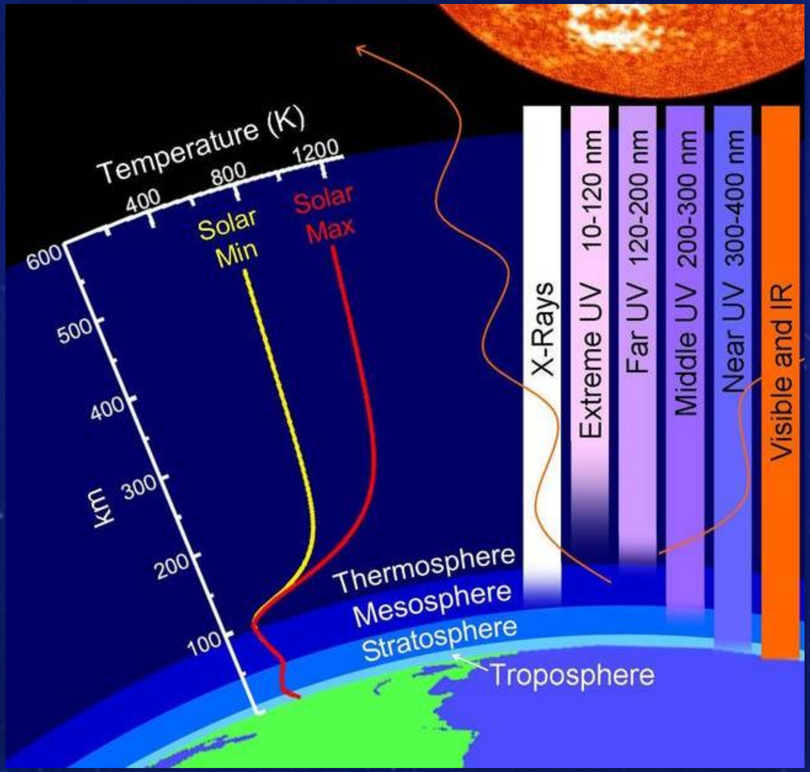
Solar EUV irradiance → Major source of thermosphere density variations

↓

Change of density → Atmospheric drag change

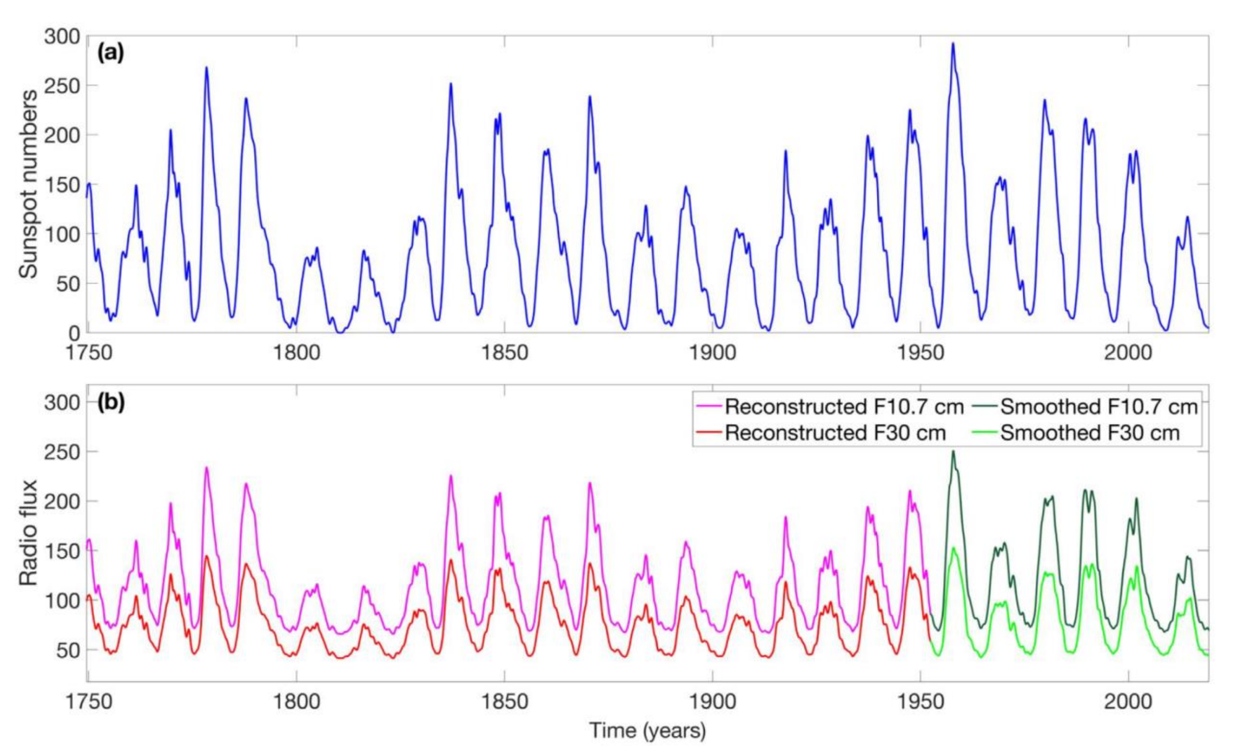
↓

Decay and following re-entry



Properties of Earth's atmosphere, NASA

Data Preparation



- ✓ **F10.7/F30 cm** is a measurement of **the total solar emission** at a wavelength of **10.7/30 cm** from all sources present on the solar disk averaged over an hour.
- ✓ **Smoothing** of monthly mean data using optimized smoothing technique (Podladchikova et. all, 2017)
- ✓ Reconstruction of F10.7 and F30 using **sunspot numbers** and 3d order linear regression

F30 cm radio flux: Toyokawa & Nobeyama Observatories, Japan

F10.7 cm radio flux: Ottawa and Pentincton Observatory, Canada

$$1 \text{ sfu} = 10^{-22} \text{ Wm}^{-2}\text{Hz}^{-1}$$

Tapping, 2013; Dudok de Wit and Bruinsma, 2017

Radio flux predictions with McNish-Lincoln method

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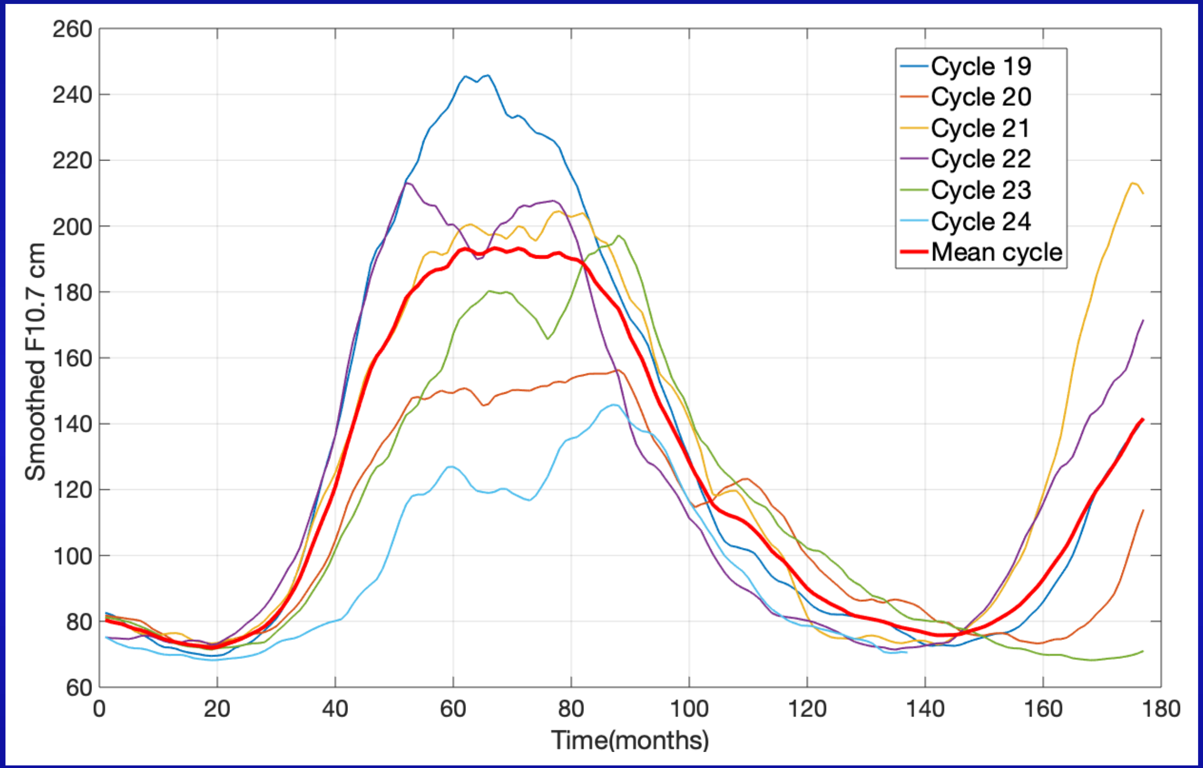
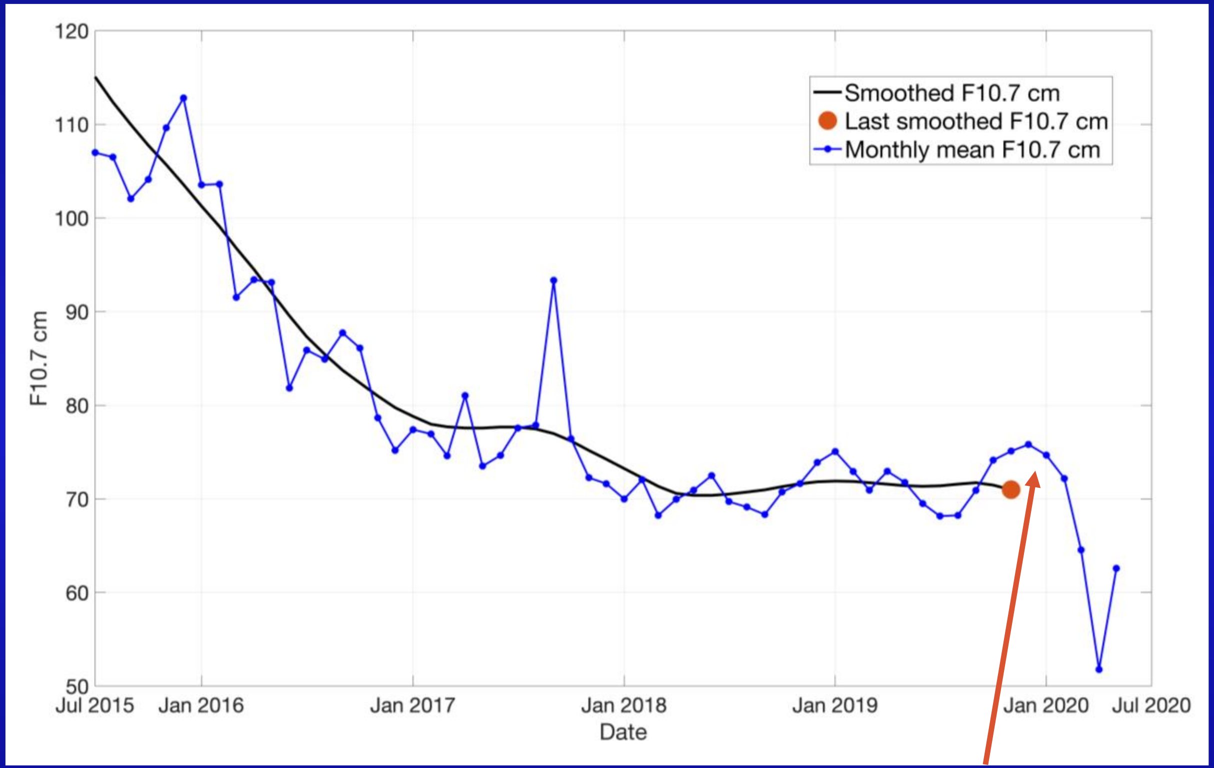




Mean cycle – average of all cycles smoothed solar radio flux aligned on the month of the minimum

Prediction for month m :

last smoothed value (month i)

$$\boldsymbol{F_m = \overline{F}_m + k_{mi}(F_i - \overline{F}_i)}$$

mean value (month m)

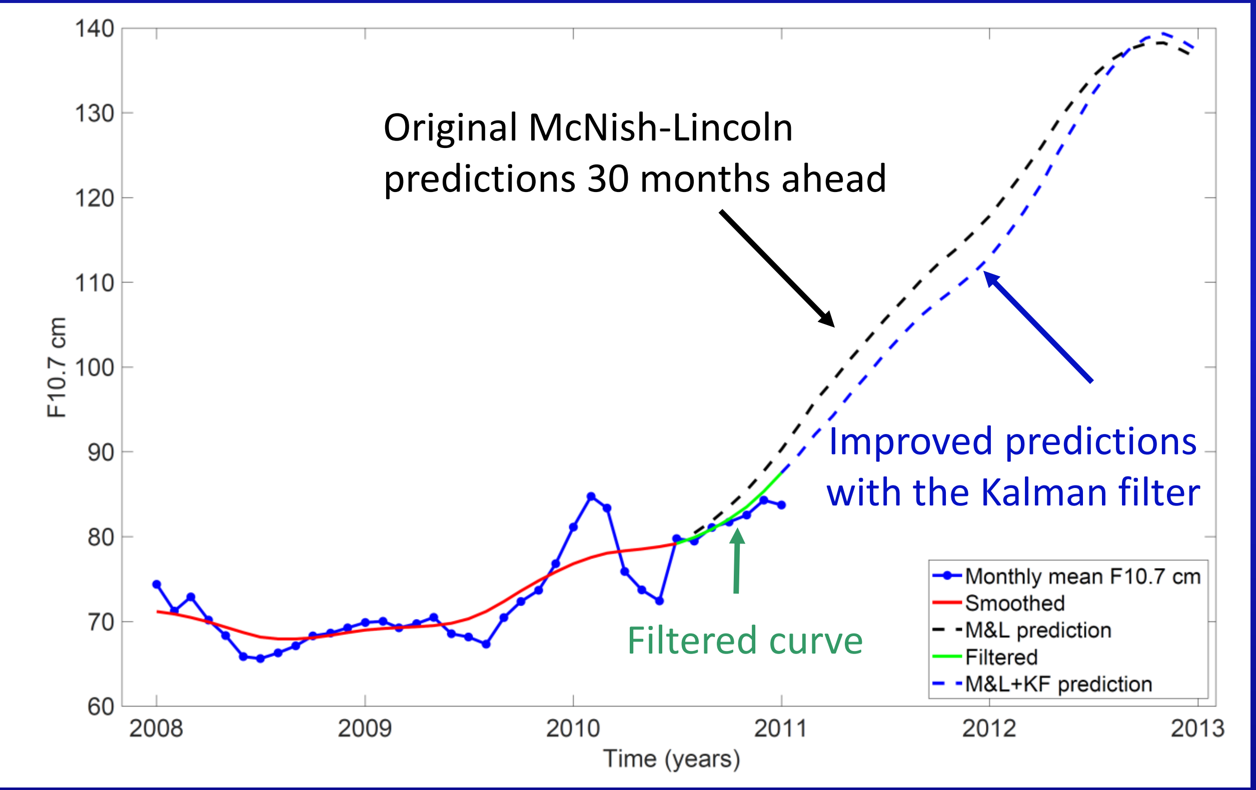
mean value (month i)

Drawback

Available with the **6-month delay** with respect to **the current time**.

McNish and Lincoln, 1949

Improvement of initial McNish-Lincoln predictions with the adaptive Kalman filter



We remove the drawback of a 6-month delay

Main idea

To **assimilate** the monthly mean radio flux data available over the last 6-month period and estimate **the smoothed radio flux at the current time**.

Apply McNish-Lincoln method again, but use the **estimated smoothed radio flux at the current time** as the starting point for the predictions.

The improvements in prediction accuracy with application of the McNish–Lincoln + Kalman filter reach **36% for F10.7** and **39% for F30.**

The **RMS error of predictions** with lead times from 1 to 24 months is **5–27 solar flux units (sfu) for the F10.7** and **3–16 sfu for F30**.

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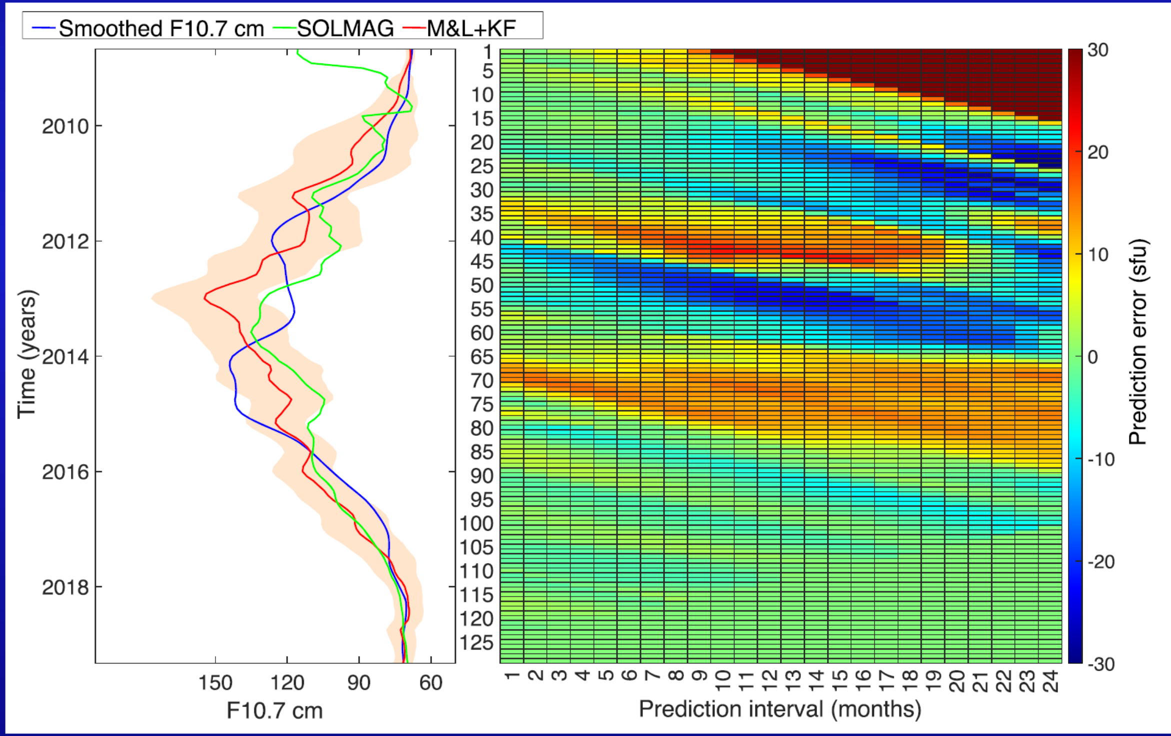
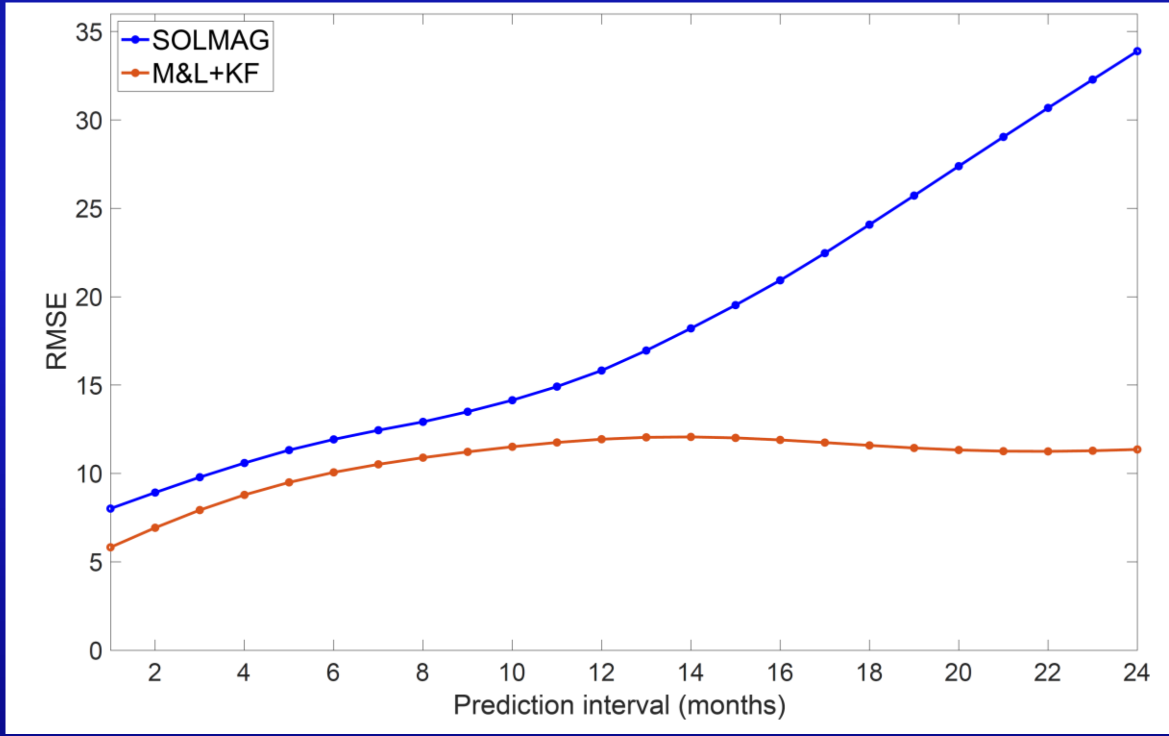
Performance results for solar cycle 24

F10.7 predictions
12 months ahead

Heat map:
>0: RESONANCE outperforms
<0: SOLMAG outperforms

Root-mean square error of prediction
1-24 month ahead (in sfu)





SOLMAG – short and long-term solar and geomagnetic activity prediction developed and currently employed by ESA

Mugellesi-Dow et al. 1993; Bastida Virgili et al. 2014

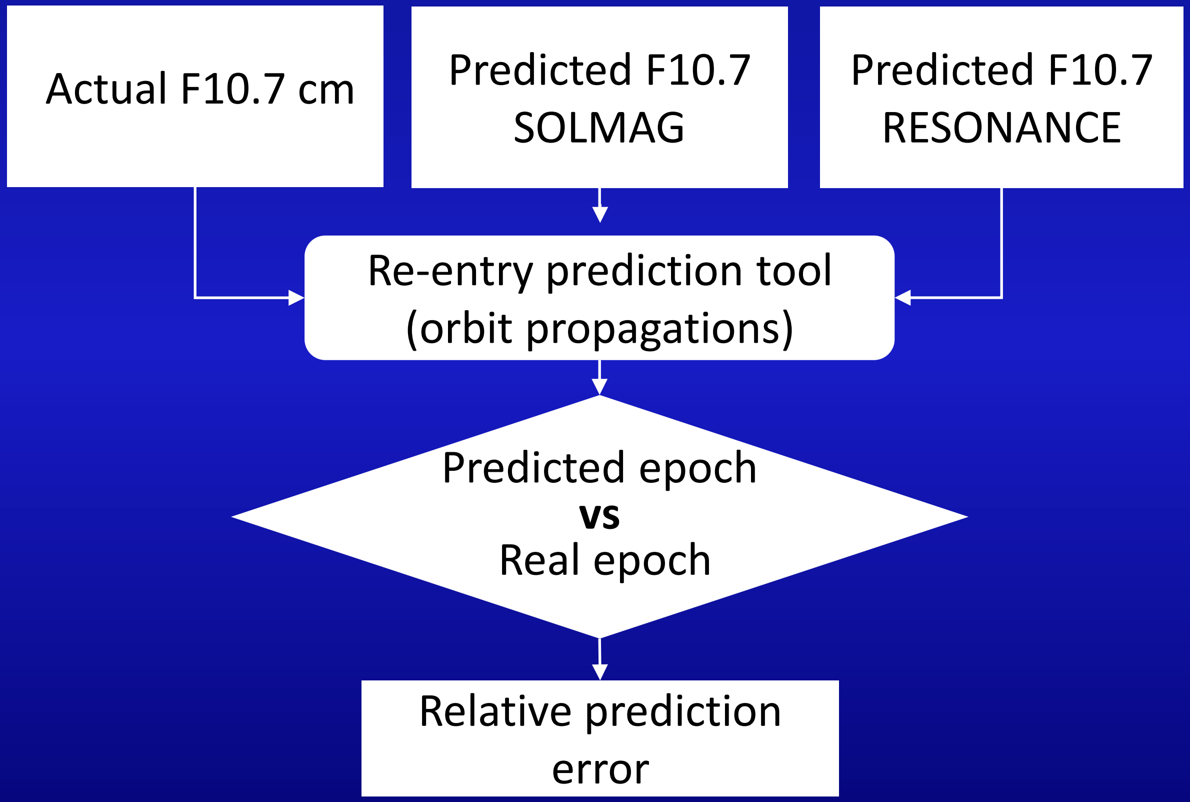
RESONANCE (M&L+KF) statistically outperforms the ESA SOLMAG method by 15.5-66.5%.

Re-entry predictions with past ESA re-entry campaigns

The objects re-entered over 2006-2019, covering the period over **the full solar cycle**.

- ✓ **602 payloads and rocket bodies** (1635 predictions)
- ✓ **2344 objects of space debris** (9584 predictions)

Recovered space debris, ESA



- ✓ On average **2 small tracked objects** (< 1 m) re-enter the Earth atmosphere and burn up **every day.**
- ✓ Objects of **moderate size** (> 1 m) – **once a week.**
- ✓ **Large** objects (heavy science satellites) **few times in a year.**

Systematic evaluation of re-entry predictions using actual F10.7 as an input

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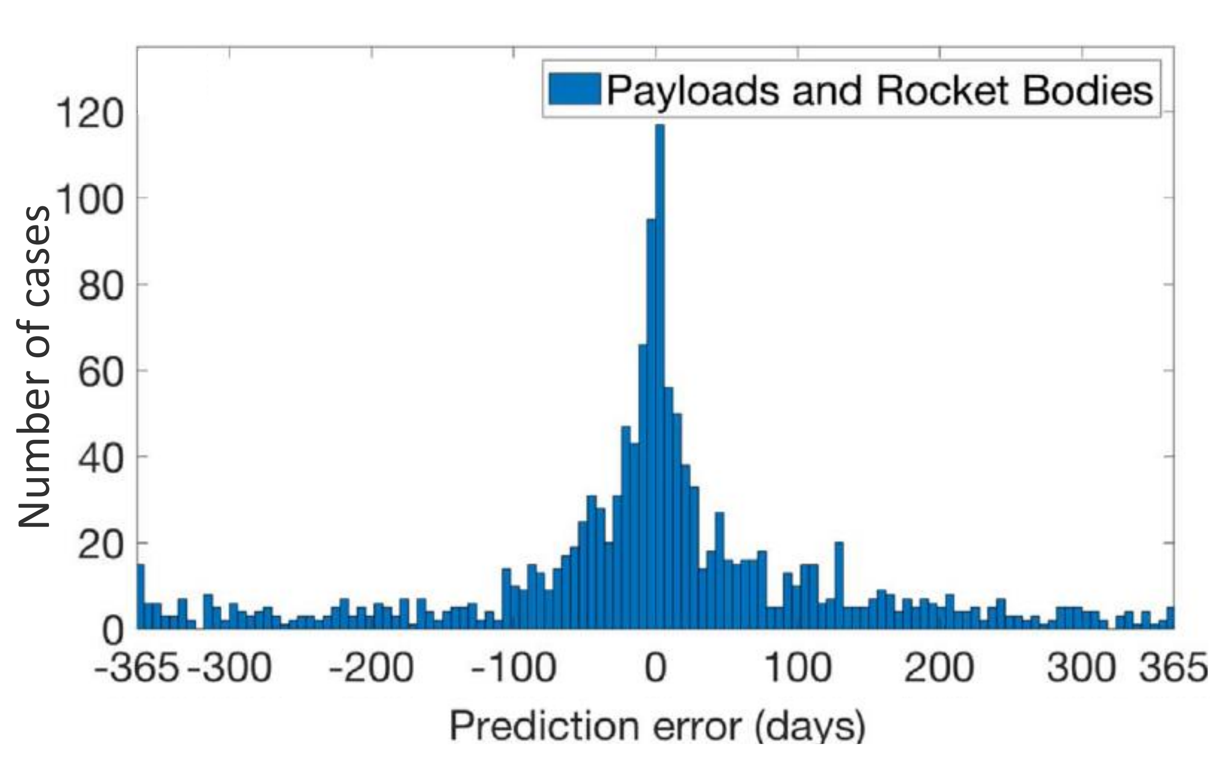
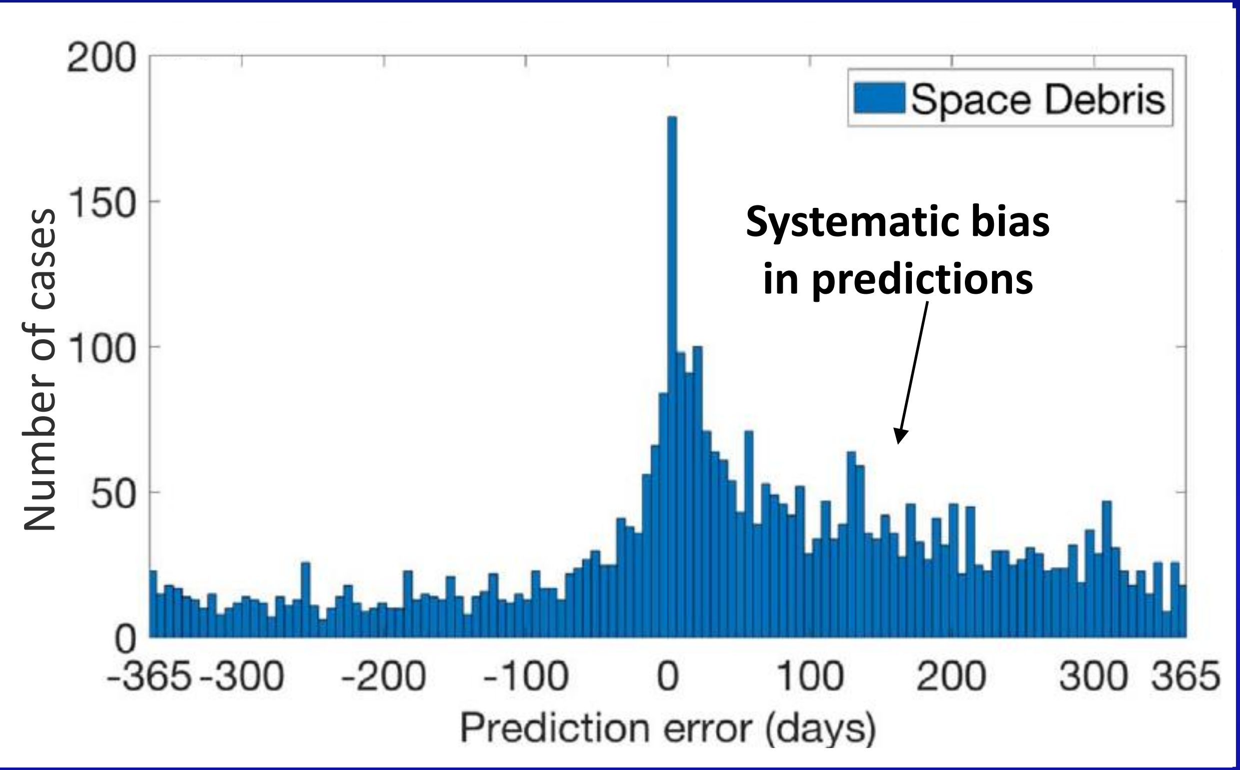
Positive/negative errors show cases of the re-entry observed earlier (later) than its prediction.





16% of cases have the absolute error of re-entry prediction more than **365 days**

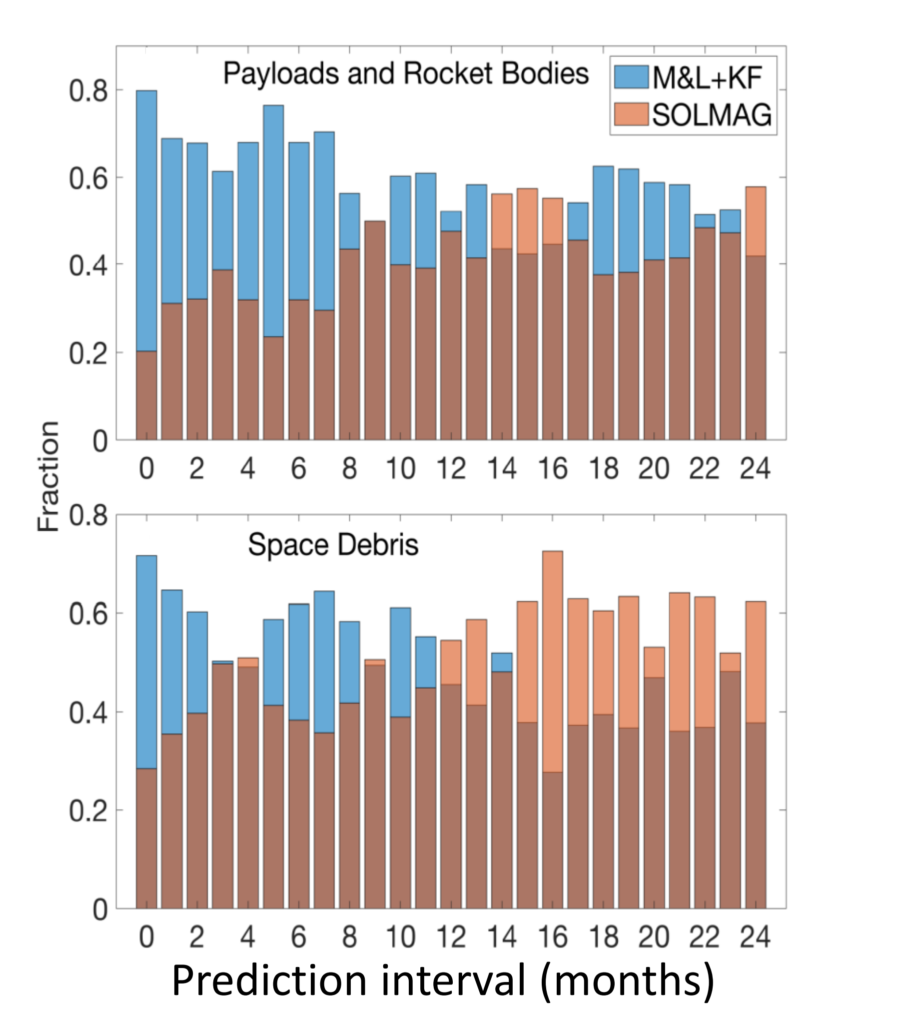
61% of cases have the absolute error of re-entry prediction more than **365 days**

Comparison of re-entry predictions using predicted F10.7 as an input

Fraction of all the forecasts, where

RESONANCE (M&L+KF) outperforms

SOLMAG outperforms non-advantageous



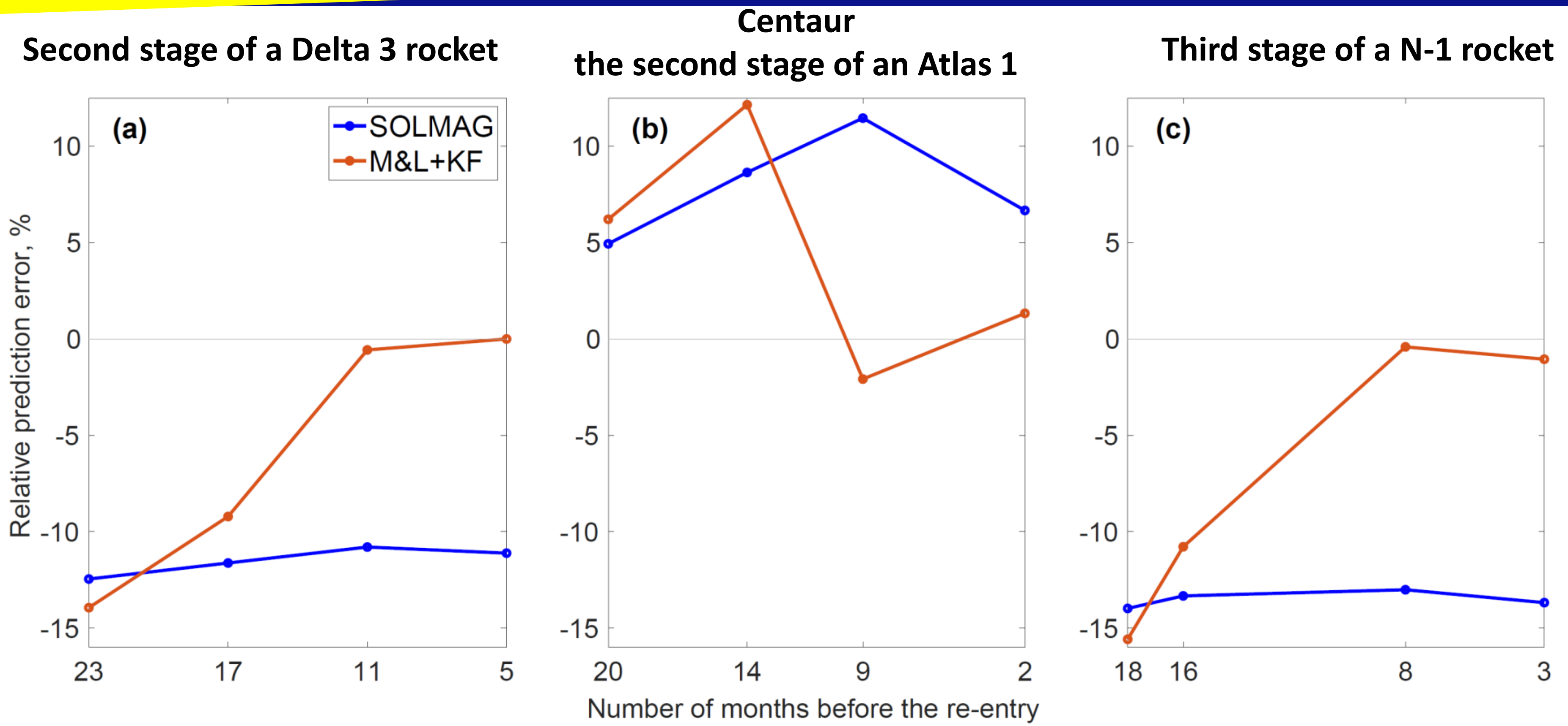
RESONANCE (M&L+KF) provides **a larger fraction** of **more accurate re-entry forecast** compared to the **SOLMAG** method.

Majority of predicted re-entries are observed at the second half of the cycle

Our approach provides **a larger fraction** of **more accurate re-entry forecast** compared to the SOLMAG method for the prediction lead times 1-11 months ahead.

Majority of predicted re-entries are observed at the first half of the cycle

Example of re-entry predictions for three rocket bodies



A negative error - predictions are earlier than the re-entry.

5-month lead forecast
Re-entry time: 29-Dec-2008
SOLMAG: 10-Dec-2008
RESONANCE (M&L+KF): 28-Dec-2008

Improvement – 18 days

9-month lead forecast
Re-entry time: 20-Oct-2014
SOLMAG: 22-Nov-2014
RESONANCE (M&L+KF): 14-Oct-2014

Improvement – 27 days

8-month-lead forecast
Re-entry time: 9-Mar-2009
SOLMAG: 5-Feb-2009
RESONANCE (M&L+KF): 8-Mar-2009

Improvement – 31 days

Summary

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- ✓ **RESONANCE** statistically **outperforms** the currently used ESA SOLMAG method by 15.5-66.5% and in general leads to improvements of re-entry predictions, and thus can be recommended for the real-time implementation.
- ✓ The proposed approach based on **the Kalman filter** is **universal** and can be applied to improve the initial predictions of a process under study provided **by any other forecasting method**.
- ✓ **Re-entry predictions** with **F30** as an input could be more accurate, as **F30** may be a **better proxy** for **the atmosphere modeling** (Dudok de Wit et al. 2014), and it is **better predictable** than F10.7.
- ✓ **The further improvement** of the re-entry forecast should include both refinements of the atmospheric models and solar activity predictions.

Petrova E., T. Podladchikova T., A. Veronig, S. Lemmens, B. Bastida Virgili, T. Flohrer (2021), Medium-term predictions of F10.7 and F30 cm solar radio flux with the adaptive Kalman filter, The Astrophysical Journal Supplement Series, 254,9, 10.3847/1538-4365/abef6d.

THANK YOU!