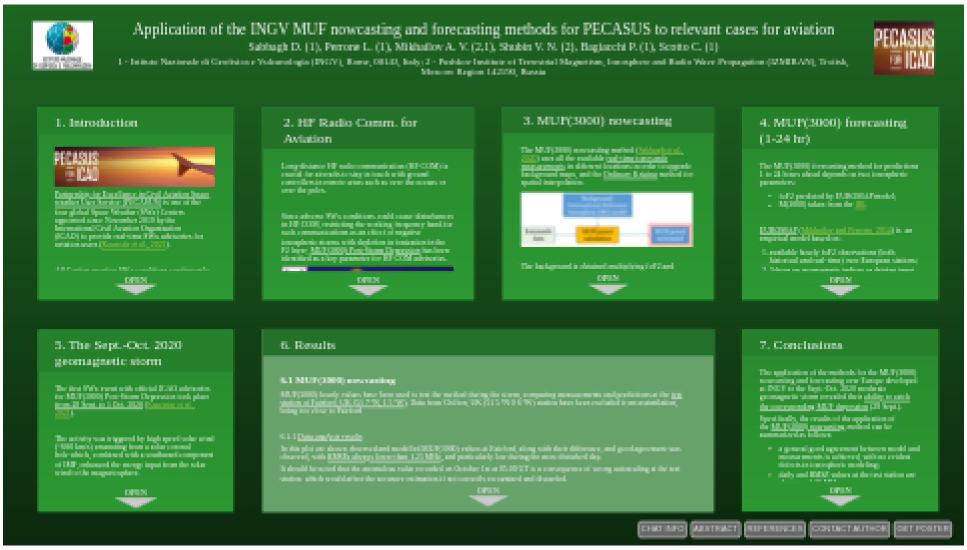
Application of the INGV MUF nowcasting and forecasting methods for PECASUS to relevant cases for aviation



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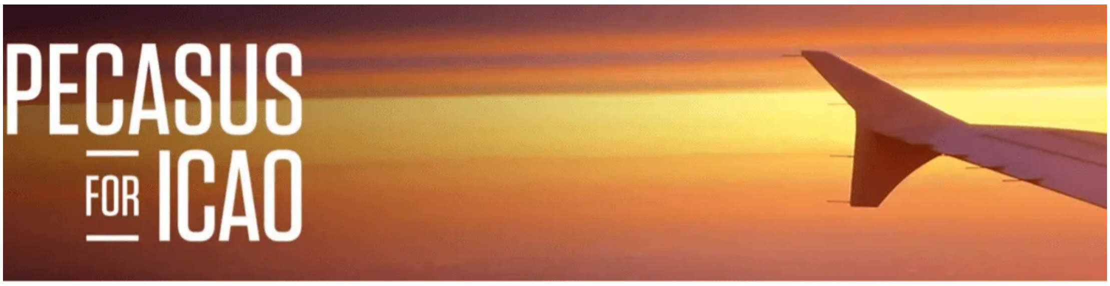
PRESENTED AT:

1. INTRODUCTION

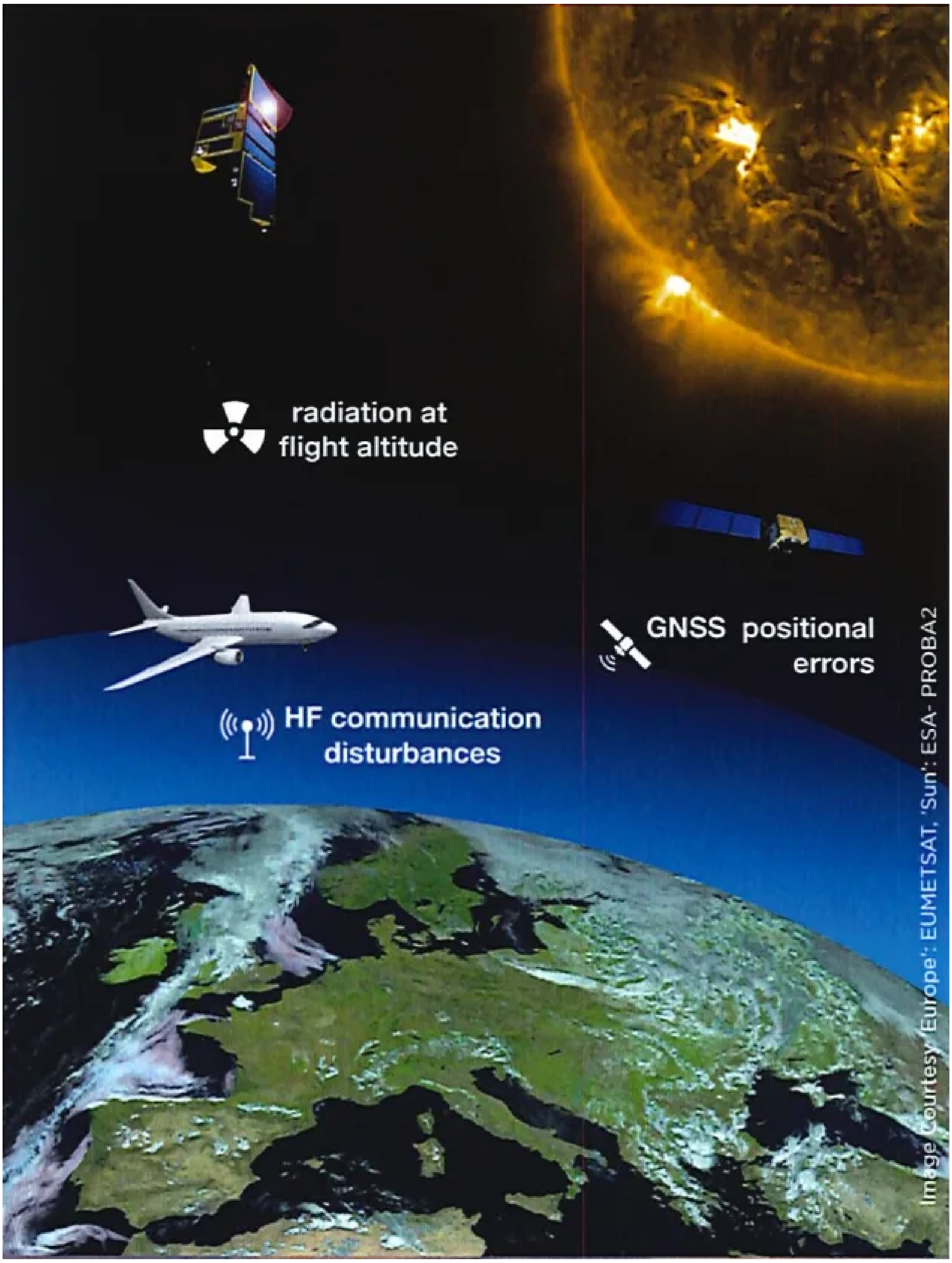


Partnership for Excellence in Civil Aviation Space weather User Service (PECASUS) is one of the four global Space Weather (SWx) Centers appointed since November 2019 by the International Civil Aviation Organization (ICAO) to provide real-time SWx advisories for aviation users (Kauristie et al., 2021 (https://doi.org/10.3390/rs13183685)).

All Centers monitor SWx conditions continuously, and share the responsibility of the advisory validation and dissemination according to a two-week shift scheme.

The three main impact areas of interest for the ICAO are:

- radiation levels at flight altitudes (RAD);
- GNSS-based navigation and positioning (GNSS);
- HF communication (HF COM);
- Satellite communication (SATCOM, *advisories currently not provided for this effect*).

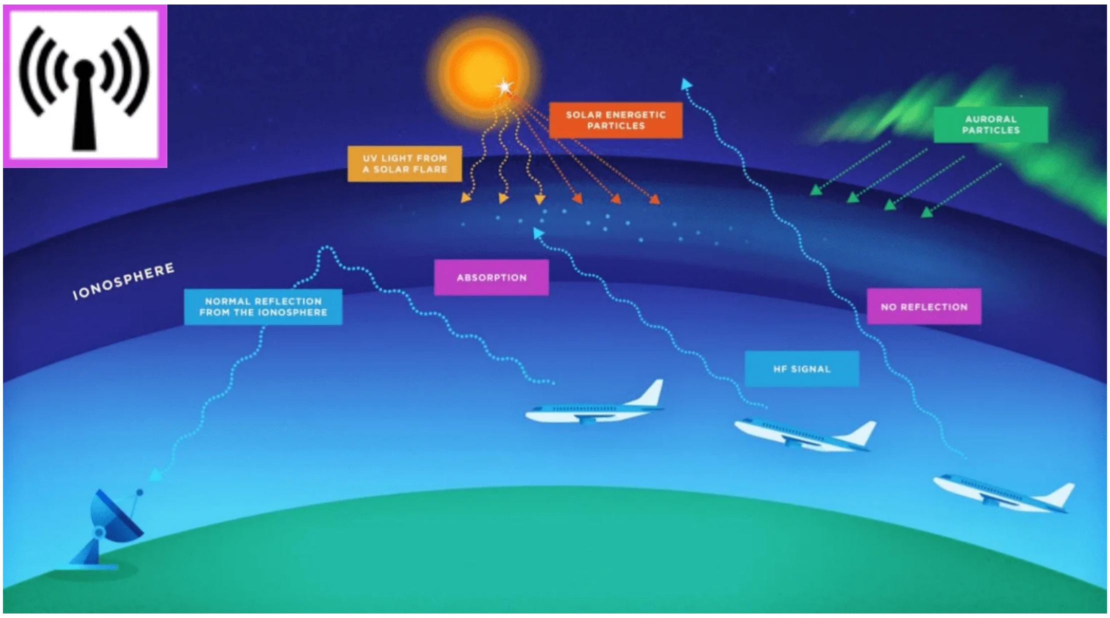


In this work European MUF(3000) nowcasting and forecasting (1-24 hr) operational products in the HF COM domain developed by INGV are presented, along with their application to the first event with official ICAO advisories.

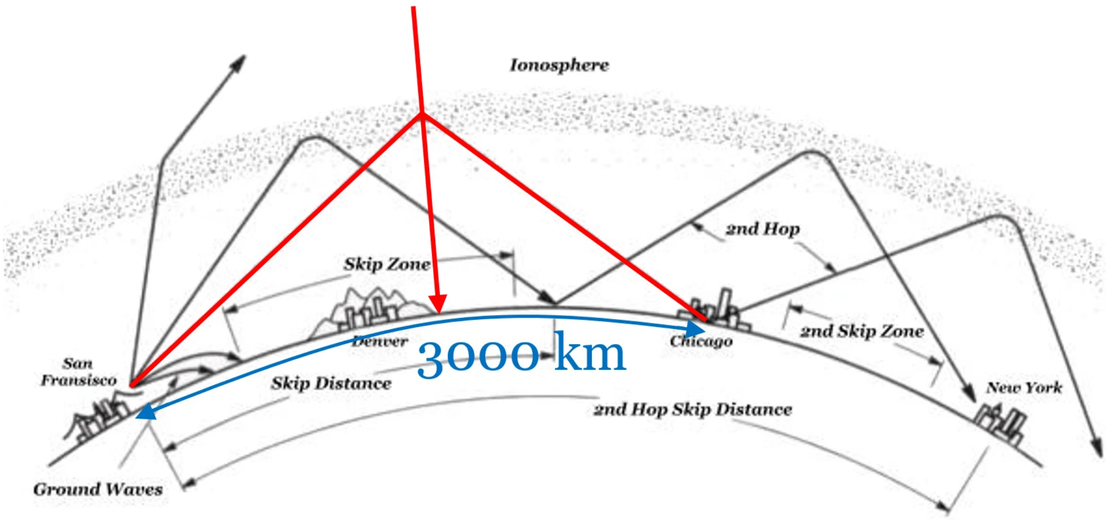
2. HF RADIO COMM. FOR AVIATION

Long-distance HF radio communication (HF COM) is crucial for aircrafts to stay in touch with ground controllers in remote areas such as over the oceans or over the poles.

Since adverse SWx conditions could cause disturbances in HF COM, restricting the working frequency band for such communications as an effect of negative ionospheric storms with depletion in ionization in the F2 layer, MUF(3000) Post-Storm Depression has been identified as a key parameter for HF COM advisories.

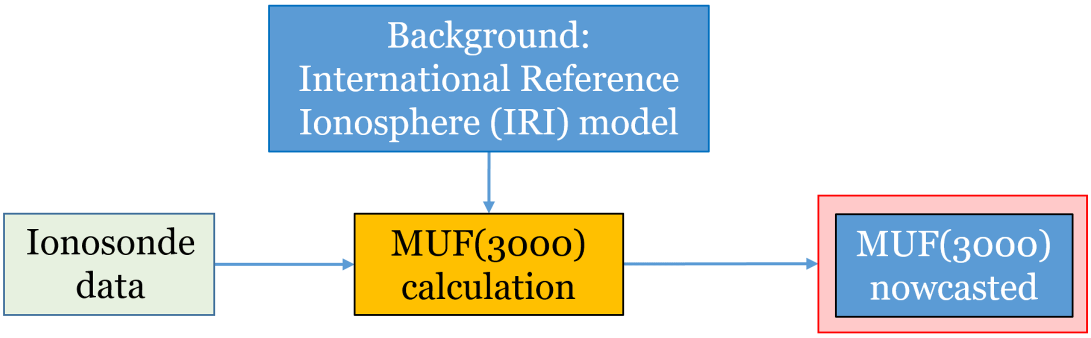


MUF(3000) is the maximum frequency that can be used for communications over a standard distance of 3000 km through ionospheric reflection by the F2 layer, and can be estimated by ionosonde measurements assuming the ionosonde location under the reflection point of the signal.



3. MUF(3000) NOWCASTING

The MUF(3000) nowcasting method (Sabbagh et al., 2020 (https://www.ursi.org/proceedings/procGA20/papers/YSAsummarysabbaghCorr.pdf)) uses all the available real-time ionosonde measurements in different locations in order to upgrade background maps, and the Ordinary Kriging method for spatial interpolation.



The background is obtained multiplying foF2 and M(3000) from IRI (http://irimodel.org/)-CCIR model (Bilitza, 2018):

$$MUF(3000)_{bkg} = f_oF2_{IRI} \cdot M(3000)_{IRI}$$

The "MUF(3000) calculation" block consists in the following steps.

1. Computation of the relative difference:

$$z(x_i) = \frac{MUF(3000)_{obs}(x_i) - MUF(3000)_{bkg}(x_i)}{MUF(3000)_{bkg}(x_i)}$$

where ionosonde autoscaled measurements are available (i-indexed).

2. Spatial interpolation of z by Ordinary Kriging at the region grid points (j-indexed).

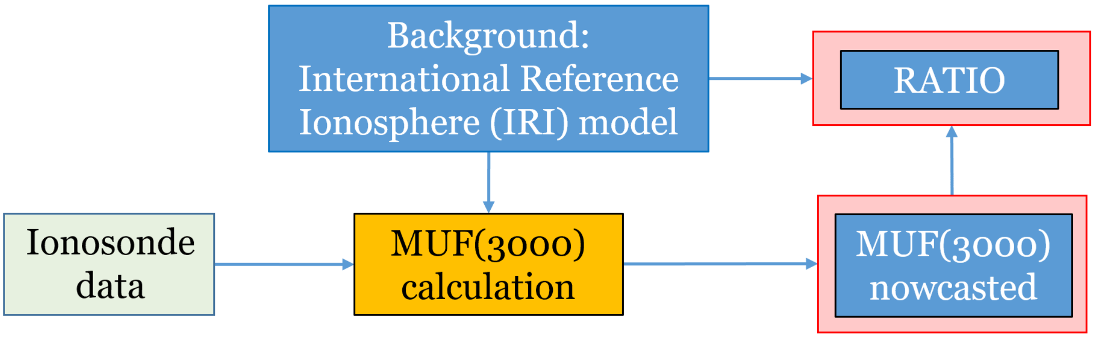
3. MUF(3000) computation at the same grid points as:

$$MUF(3000)(x_j) = (1 + z(x_j)) \cdot MUF(3000)_{bkg}(x_j)$$

Dividing the MUF(3000) modelled values by the background, maps of MUF(3000) ratio:

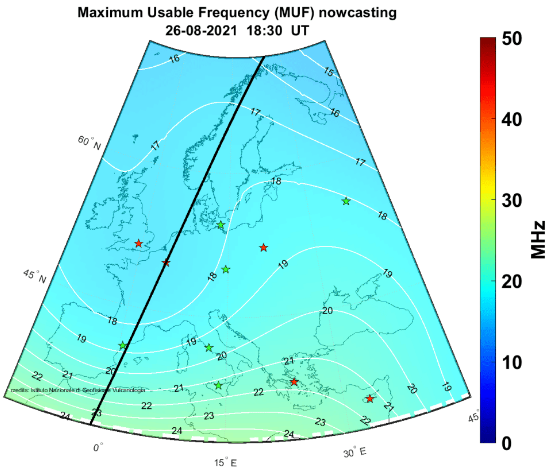
$$MUF(3000)_{rat}(x_j) = \frac{MUF(3000)(x_j)}{MUF(3000)_{bkg}(x_j)}$$

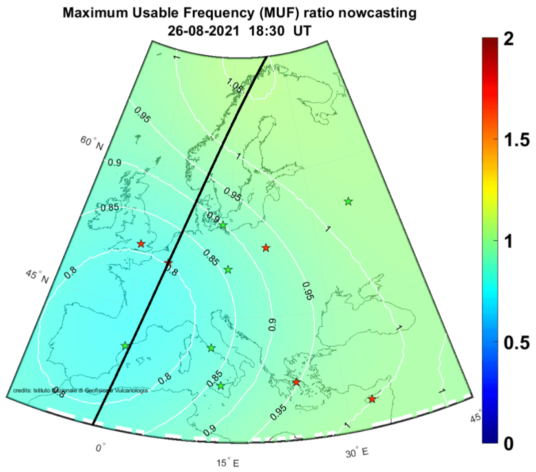
are also created over the same area.



This lets to immediately detect regions of MUF(3000) depletion with respect to the background level, and possibly issue the corresponding advisory in accordance with the thresholds based on ICAO requirements.

This is an example of maps for 26 August 2021, 18:30 UT.





Green stars represent the locations of used measurements, while red ones indicate the stations where data were not available in real-time for that specific time. The continuous black line indicates the position of the solar terminator, and the color scale lets us easily identify regions of MUF depression from ratio maps, associated to blue color.

Such maps are created and delivered to PECASUS with the following specifications.

- Spatial coverage: 12°W-45°E lon; 32°N-72°N lat
- Spatial resolution: 0.5° x 0.5°
- Update rate: 15 min
- Format: .png and .json

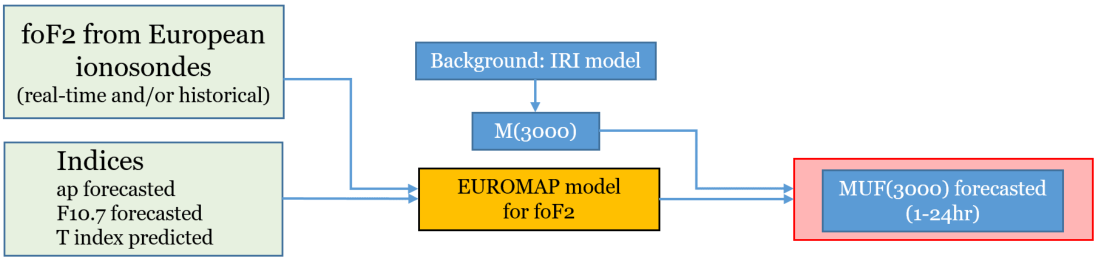
F(3000) FORECASTING (1-24 HR)

The MUF(3000) forecasting method for predictions 1 to 24 hours ahead depends on two ionospheric parameters:

- foF2 predicted by EUROMAP model;
- M(3000) taken from the IRI (http://irimodel.org/).

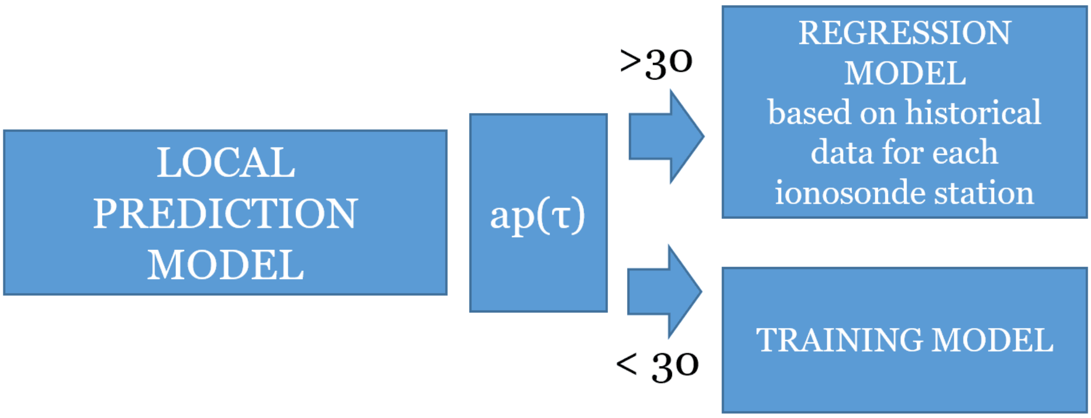
EUROMAP (Mikhailov and Perrone, 2014 (https://doi.org/10.1002/2014RS005373)) is an empirical model based on:

1. available hourly foF2 observations (both historical and real-time) over European stations;
2. 3-hour ap geomagnetic indices as driving input parameter;
3. F10.7 for locations far from the stations;
4. effective ionospheric monthly T indices to specify the background level.

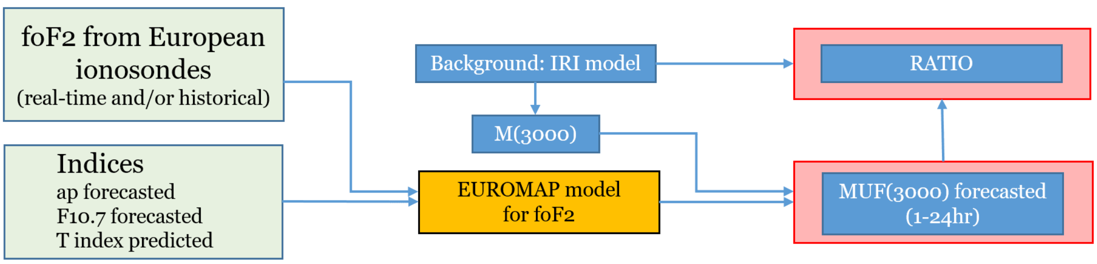


Local Prediction Models have been created for each European ionospheric station, depending on the value of ap(τ), which considers also the ap values for the previous hours.

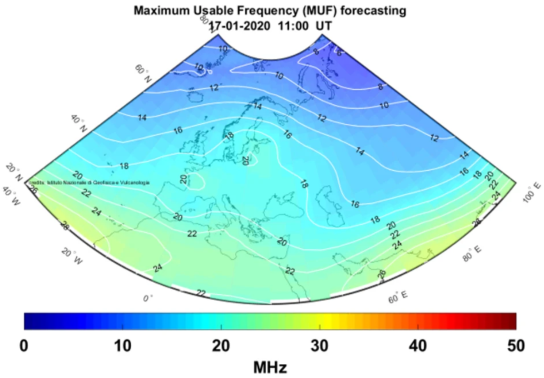
Specifically, for ap(τ)<30 a Training Model is used, based on foF2 values for the previous hours, while a Regression Model, based only on ap(τ), is used to describe strong negative disturbances under ap(τ)>30.

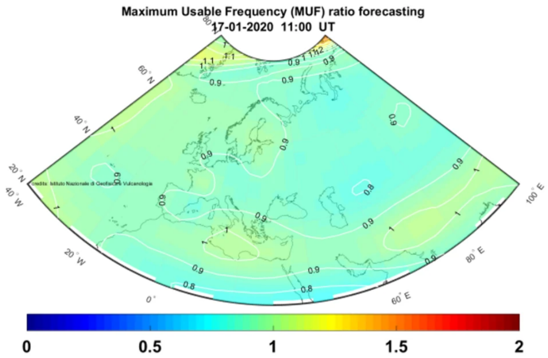


Dividing the MUF(3000) predicted values by the background, maps of MUF(3000) ratio are created also in this case.



This is an example of maps for 17 January 2020, 11:00 UT.





Such maps are created and delivered to PECASUS with the following specifications.

- Spatial coverage: 40°W-100°E lon; 20°N-80°N lat
- Spatial resolution: 2.5° lat x 5.0° lon
- Update rate: 60 min
- Predicted time: 1-24 hours ahead
- Format: .png and .json

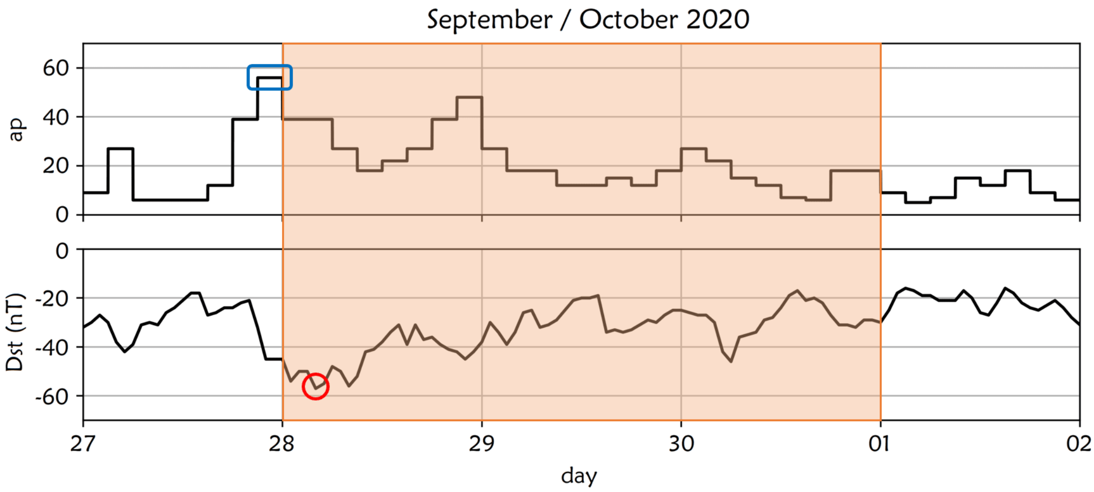
Note that the spatial extension of such maps is larger than nowcasted maps, thanks to the lower dependence to real-time observations from the ionospheric stations.

5. THE SEPT.-OCT. 2020 GEOMAGNETIC STORM

The first SWx event with official ICAO advisories for MUF(3000) Post-Storm Depression took place from 28 Sept. to 1 Oct. 2020 (Kauristie et al., 2021 (https://doi.org/10.3390/rs13183685)).

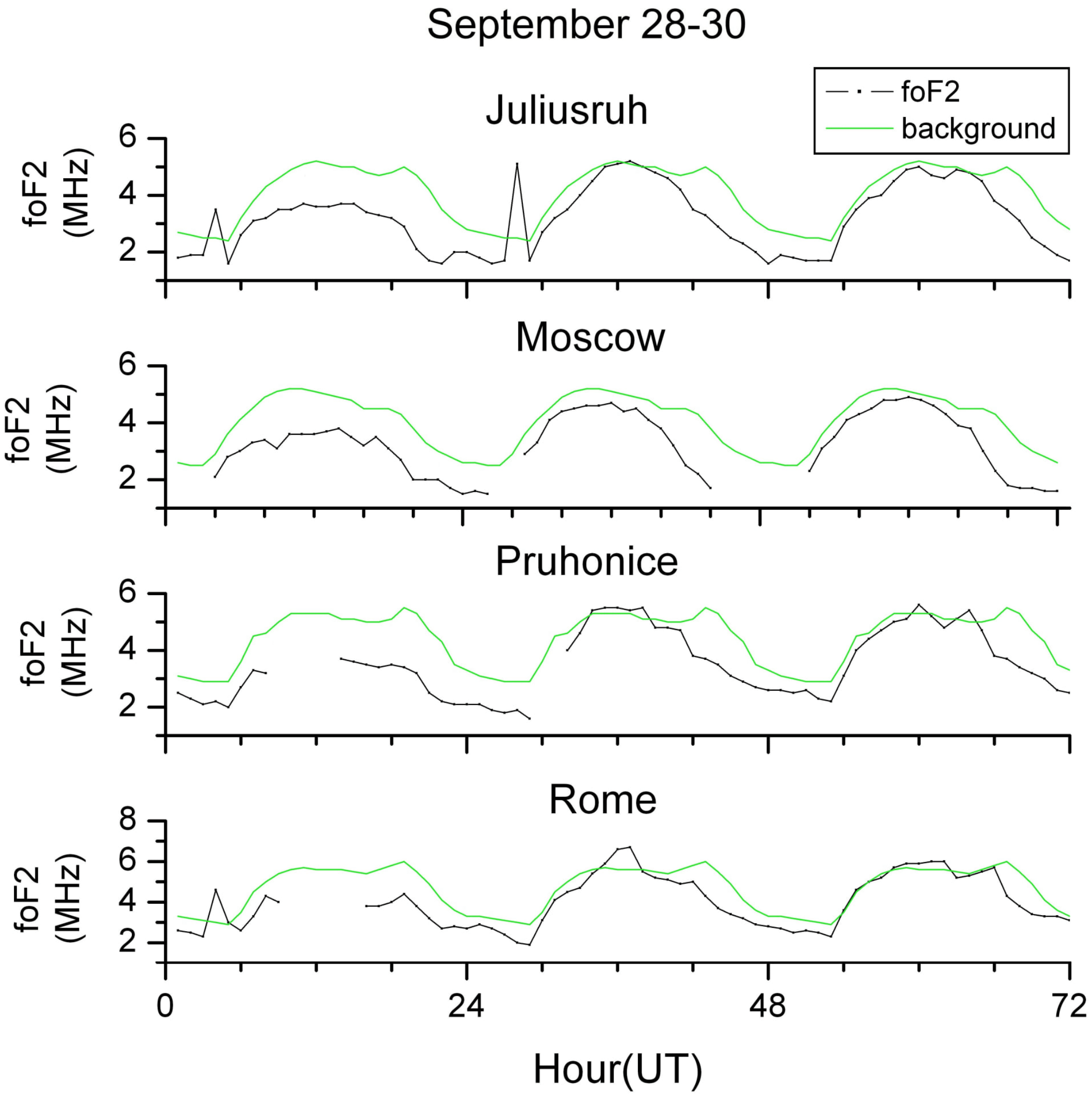
The activity was triggered by high speed solar wind (~600 km/s) emanating from a solar coronal hole which, combined with a southward component of IMF, enhanced the energy input from the solar wind to the magnetosphere.

A moderate geomagnetic storm arised, with a maximum ap value of 56 (i.e. Kp=5+) during the three last UT hours of 27 Sept. 8 (blue square), while the Dst index reached a minimum of -57 nT at 04:00UT on 28 Sept. (red circle). Enhanced geomagnetic activity (Kp 4-5) continued still throughout the day on 28 Sept., but the activity ceased during the next days.



The first signs of Post-Storm Depression were observed around 05:30 UT on 28 Sept. by the Australia-Canada-France-Japan consortium (ACFJ), which served as the on-duty center at that time. During the event ACFJ sent altogether 13 advisories about subsequent depressions in different regions of the globe over a period of 3.5 days.

In particular, depression was observed in the Central European sector (lat 42°-55ºN; lon 14°-30°E) on the period 28-30 Sept., when moderate Post-Storm Depression took place during both daytime and nighttime.


September 28-30
Juliusruh
Moscow
Pruhonice
Rome
foF2
background
foF2 (MHz)
Hour(UT)
0
24
48
72

6. RESULTS

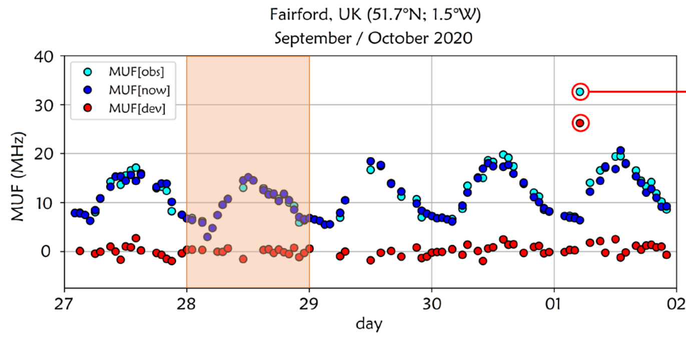
6.1 MUF(3000) nowcasting

MUF(3000) hourly values have been used to test the method during the storm, comparing measurements and predictions at the test station of Fairford, UK (51 7 ºN, 1 5 ºW). Data from Chilton, UK (51 5 ºN 0 6 ºW) station have been excluded from assimilation, being too close to Fairford

6.1.1 *Data analysis results*

In this plot are shown observed and modelled MUF(3000) values at Fairford, along with their difference, and good agreement was observed, with *RMSE*s always lower than 1.25 MHz, and particularly low during the most disturbed day.

It should be noted that the anomalous value recorded on October 1st at 05.00 UT is a consequence of wrong autoscaling at the test station, which would affect the accuracy estimation if not correctly recognized and discarded.

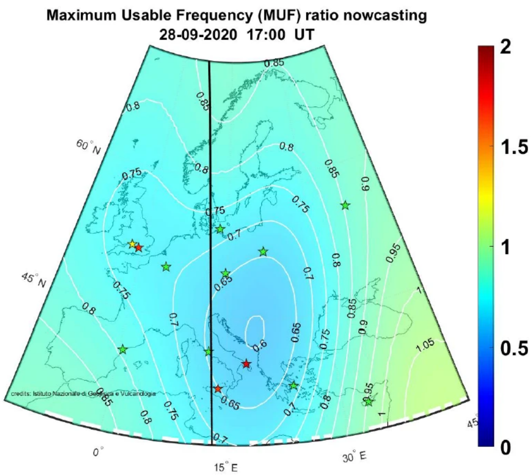


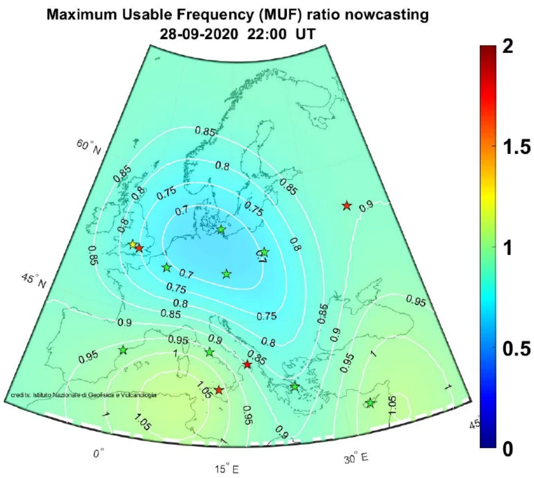
	Fairford	
	RMSE (MHz)	*n*
27/9/2020	1.20	14
28/9/2020	0.62	14
29/9/2020	0.98	8
30/9/2020	1.17	15
1/10/2020	1.25 (6.67)	15 (16)
Total	1.08 (3.38)	66 (67)

wrong autoscaling affects the results

6.1.2 *Observed depression on 28 Sept. from maps*

As can be seen from these maps of example, a depression from about 30% to 45% is observed on 28 Sept. in the European region, as a result of the upgrade of the background model with the data of 8-9 stations in the area.





6.1.3 *Rejection and failures*

Some cases are automatically discarded by the procedure:

1. number of assimilated stations < 4;
2. failure of variogram fitting (on the basis of the usual Q1 and Q2 statistical tests);

3. “bad” map (i.e. uniform ratio map with unitary ratio everywhere).

In particular, we can consider the two last cases as failures of the procedure, because something goes wrong within the Kriging procedure.

	# of automatic rejections (reasons 2 & 3)	# of manual rejections (reason 3)	# of total failures	% of total failures
27/9/2020	6	1	7	29.17 %
28/9/2020	4	2	6	25.00 %
29/9/2020	10	2	12	50.00 %
30/9/2020	5	4	9	37.50 %
1/10/2020	7	1	8	33.33 %
Total	32	10	42	43.75 %

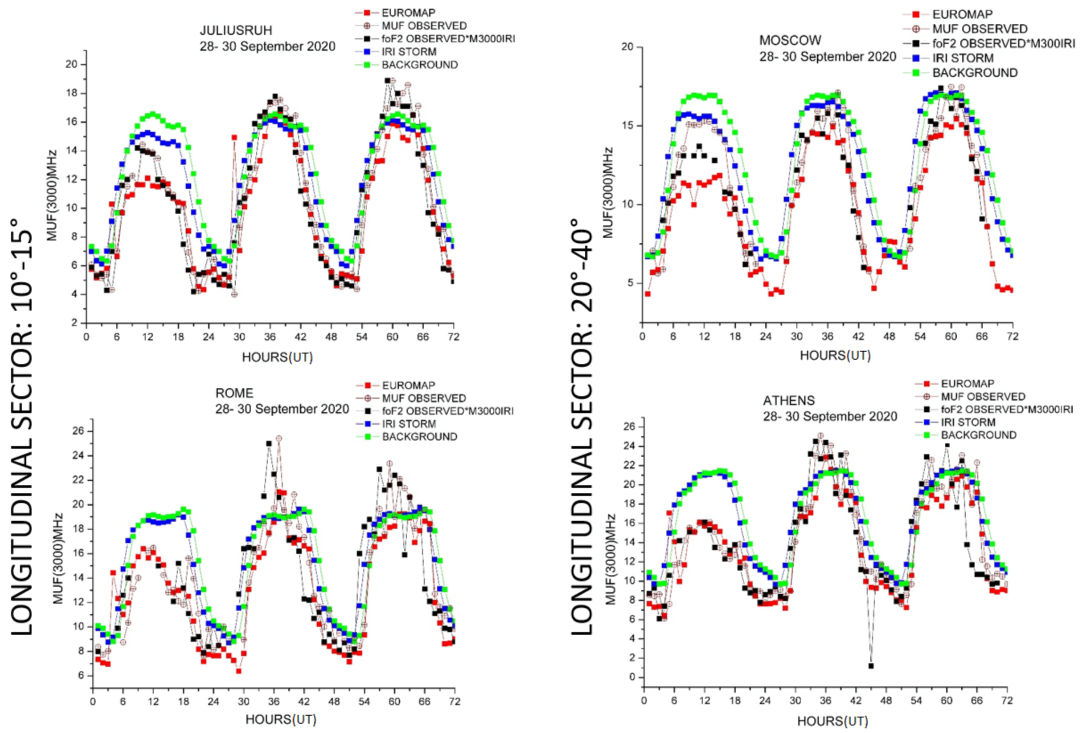
In this case, there are no a-priori rejections (reason 1) thanks to the good number of available data, which is not always the case for near real-time application of the method.

Conversely, a percentage of failures (reason 2 and 3) of 40% arised. Besides, automatic rejection for reason 3 is not fully efficient, and some “bad” maps are still created.

6.2 MUF(3000) forecasting (1-24 hr)

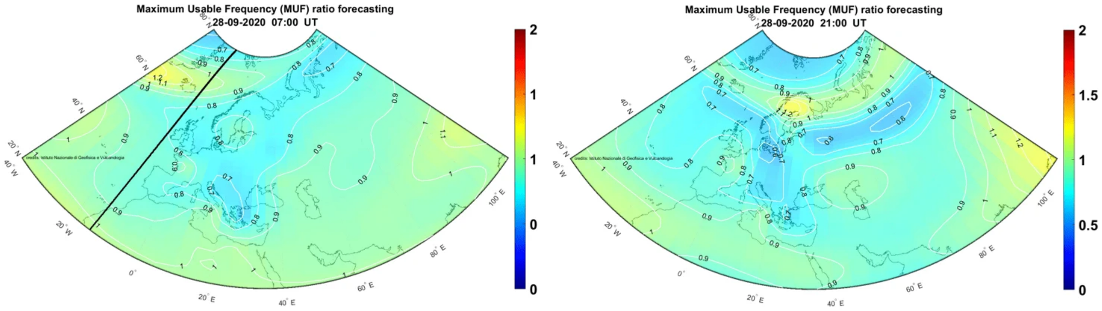
6.2.1 *Data analysis results*

A comparison between EUROMAP and IRI(STORM) (Araujo-Pradere et al., 2004) models (red and blue curves, respectively) with the background model (Shubin, 2017 (https://doi.org/10.1134/S0016793217040181)) (green curve), the ionosonde data (brown curve) and the product $foF2_{obs} \cdot M3000_{IRI}$ (black curve) in two different longitudnal sectors is here shown.



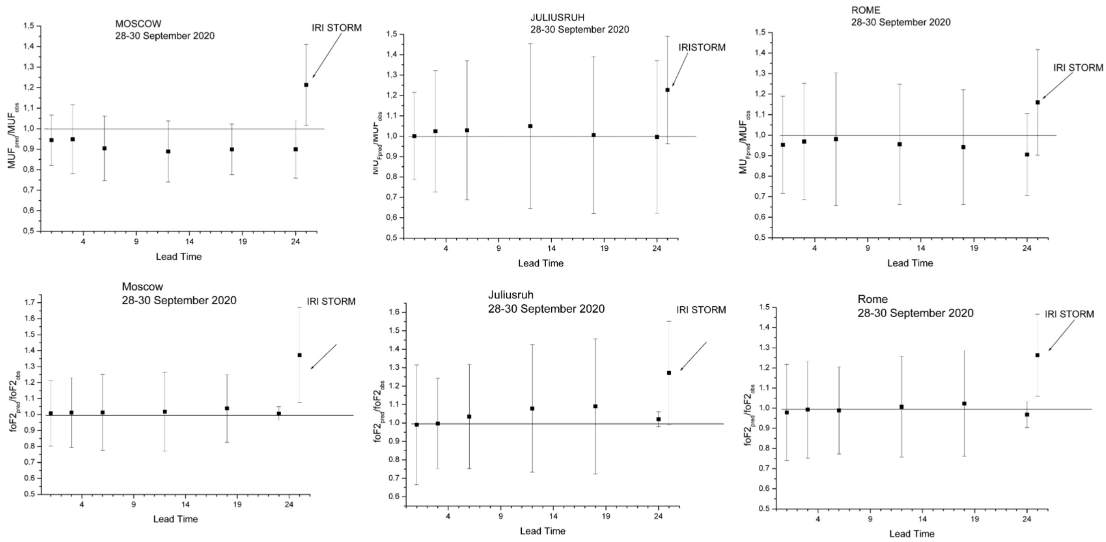
It is encouraging to notice that during this moderate negative MUF depression event, EUROMAP follows the observations much better than the IRI(STORM) model, although some signicative discrepancies are sometimes observed (see e.g. Juliusruh and Moscow on 28 Sept. during daytime).

6.2.2 *Observed depression on 28 Sept. from maps*



6.2.3 *Dependence on lead time*

Under moderate geomagnetic storm conditions EUROMAP model shows a dependence on the lead time, as also the Training Models at the stations are used. Here is shown the lead time (1–24 h) dependence of the ratios MUF_{pred}/MUF_{obs} and average $foF2_{pred}/foF2_{obs}$ (along with ±SD) observed at Moscow, Juliursuh, and Rome on 28-30 Sept.2020.



As can be seen, foF2 by EUROMAP, and MUF(3000) forecasting predictions are always better than IRI(STORM) ones. Sometimes (see e.g. Moscow), slightly worse results are obtained for MUF(3000) than foF2, due to the difference between observed MUF(3000) and those calculated using M(3000) from IRI.

Besides, better results for lead time from 1 to 3 hours, and equal to 24 hours are always obtained, probably due to the origin of the negative storm, which is related to neutral composition changes.

7. CONCLUSIONS

The application of the methods for the MUF(3000) nowcasting and forecasting over Europe developed at INGV to the Sept.-Oct. 2020 moderate geomagnetic storm revealed their ability to catch the corresponding MUF depression (28 Sept.).

Specifically, the results of the application of the MUF(3000) nowcasting method can be summarized as follows:

- a general good agreement between model and measurements is achieved, with no evident defects in ionospheric modeling;
- daily and *RMSE* values at the test station are always ≤ 1.25 MHz;
- the best accuracy is obtained during the most disturbed day (28 Sept.);
- despite the high % of total failures of the method (>40%) most cases are automatically discarded;
- erroneous data used for comparison are proved to negatively affect the accuracy assessment of the model, if not correctly detected and discarded.

The MUF(3000) short-term prediction (1-24 hr) for storm conditions over the European area gave instead the following results:

- the descriptive and prediction accuracy of the method is higher than IRI(STORM) provides;
- MUF(3000) prediction provides good result especially for lead time equal to 1-3 horrs, and 24 hours ahead;
- observed MUF(3000) is in acceptable agreement with MUF(3000) calculated by the product between foF2 and M3000 obtained from the IRI model
- MUF_{pred}/MUF_{obs} dependence versus lead time manifests an average deviation ≤ 10%;
- the least deviations for the foF2prd/foF2obs dependence versus lead time takes place in the beginning (1–3 h) and in 24 h. This peculiarity could be related to the negative disturbance formation mechanism, which is related to neutral composition changes, as the disturbance bulge “rotates” with the Earth producing a negative storm effect at the same location in 24 h (Prölss, 1995).

These results confirm that the INGV products in the HF domain can be effectively used as part of a SWx service for real-time assessment of HF radio propagation conditions over Europe.

Acknowledgements

The authors thank the Lowell DIDBase through GIRO (http://giro.uml.edu/didbase/scaled.php (http://giro.uml.edu/didbase/scaled.php)) and the Polish Academy of Science Space Research Centre to provide ionospheric data, and the Kyoto World Data Center for Geomagnetism (http://wdc.kugi.kyoto-u.ac.jp/ (http://wdc.kugi.kyoto-u.ac.jp/)) to provide geomagnetic data The Juliusruh data are kindly provided by Leibniz institute of Atmospheric Physics station Juliusruh Germany.

ABSTRACT

As it is known, Space Weather (SWx) phenomena can have dramatic impact on satellite navigation and HF radio communication systems, being also responsible for increases on radiation levels at flight altitudes. For this reason, in recent years the International Civil Aviation Organization (ICAO) has been showing great interest in operational SWx services for aviation purposes in these three domains. Four global SWx centers have been then appointed since November 2019 by ICAO to provide real-time SWx advisories for aviation users.

In particular, HF COM conditions are assessed by monitoring the F2-layer critical frequency f_oF2 or the MUF(3000) ionospheric characteristic (MUF = Maximum Usable Frequency), the latter representing the highest HF radio frequency that can be used for communications over a standard distance of 3000 km via F2-layer ionospheric reflection.

As one of the designed SWx centers, several key operational 24/7 products for HF COM conditions assessment have been developed within PECASUS (Partnership for Excellence in Civil Aviation Space weather User Services). Nowcasting and forecasting (1-24hr) maps over Europe of MUF(3000) and its ratio with respect to a background level are then developed by INGV, as a PECASUS partner.

The MUF(3000) nowcasting uses all the available real-time ionosonde measurements in different locations in order to upgrade IRI-CCIR-based background maps, and Ordinary Kriging method for spatial interpolation. The MUF(3000) modeling performance was assessed comparing predicted values to measured ones over two test stations during strong geomagnetic storm periods, obtaining an overall *RMSE* < 2 MHz at both stations.

The MUF(3000) predicted 1-24 hours ahead depends on f_oF2 and M(3000) ionospheric parameters: EUROMAP forecasting model and IRI model are used for the former and the latter, respectively. The method has been applied to Europe where there are ionospheric stations with long (for some solar cycles) historical data and current real-time f_oF2 observations. A mapping procedure applied to the European stations provides MUF(3000) short-term prediction over the whole area.

The application of these methods to storm events occurred after November 2019 is here presented, in order to study the ionospheric conditions they provide when HF COM advisories are expected to be issued.

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