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Regional short-term forecasting of ionospheric TEC and scintillation

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Summary

Model for a Regional short-term forecasting of ionospheric TEC and scintillation

- Basic features
- History of the model
- Model insights
- Model performance
- Concluding remarks

Model basic features

Regional

- to support the modeling of the ionospheric behavior with high spatial accuracy

Empirical

- because model relies on GNSS data from local network

Short-term

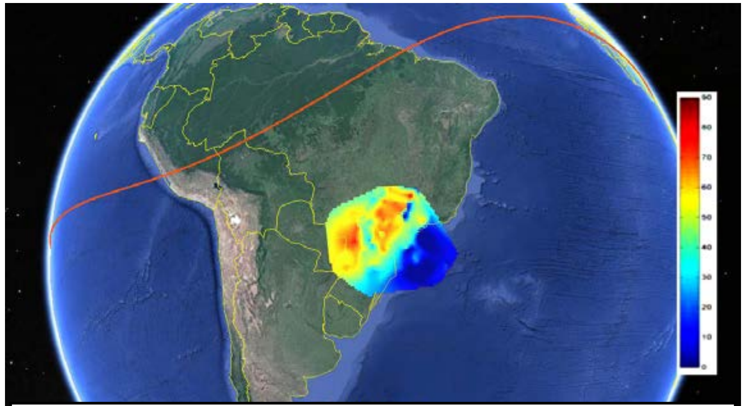
- from seconds to minutes

Forecasting of scintillation and TEC

- basic quantities describing ionospheric conditions both in terms of electron content and scintillation parameters (σ_Φ,S4, p and T)

History of the model

- The first versions were realised by INGV and CBK-PAN in the frame of the CALIBRA project
    - Funded under FP7 (lead: Nottingham University)
    - Start: Nov. 2012 – end: Feb. 2015
    - CALIBRA developed algorithms for GNSS based applications to tackle the effects of ionospheric disturbances over Brazil.
    - Legacy of the CIGALA project
    - The forecasting model were developed to supported positioning and navigation applications and services for which real time modelling and forecasting of ionospheric variability and scintillation is required
- The forecasting model were patented
    - Italian and International – patent n° 102015000015809
    - SpacEarth Technology, the INGV Spin-off company
- Ready to be integrated in firmware to support NRTK applications
    - Precision agriculture, navigation, railways management, etc.



Forecasted TEC map over São Paulo

Model insights

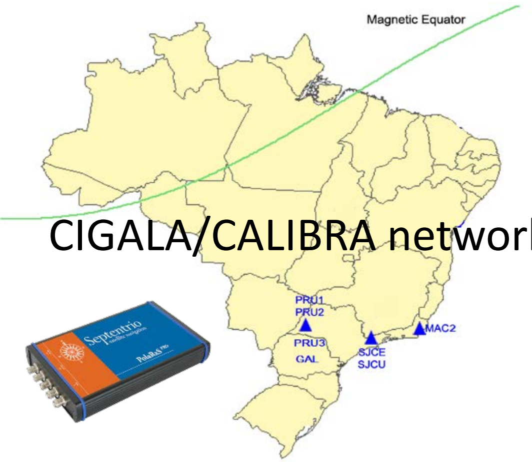
Model settings

Scintillation parameters (σ_Φ,S4, p and T)

Scint. channel

continuity equation with production/loss term

$$\frac{\partial}{\partial t}\int_V dV\, f = -\int_{\partial V} ds(f\mathbf{v}) + \int_V dV\,(p-l)$$



CIGALA/CALIBRA network

TEC calib

continuity equation without any production/loss term

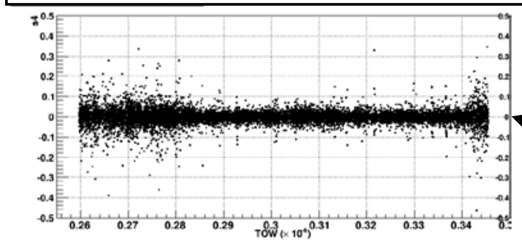
$$\frac{\partial}{\partial t}\int_V dV f = -\int_{\partial V} ds\cdot(f v)$$

TEC channel

TEC data

Model core algorithms

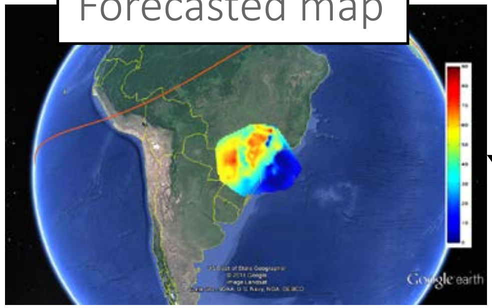
Forecasted time profiles



Example

Forecasted scintillation parameters

Forecasted map



Example

Forecasted TEC data

Model insights

- The model is based on the **transport theory for a scalar field.**
- Equation of continuity for a scalar f provided known velocity field v.

$$\frac{\partial}{\partial t}\int_V dV\, f = -\int_{\partial V} d\mathbf{s}(f\mathbf{v}) + \int_V dV\,(p-l)$$

Equation of continuity

Scalar field — *Velocity of the field* — *Source term*

V is the total volume with boundary ∂V

- The idea of the modeling is **to reconstruct the velocity field v of the given parameter** (integrated along the line of sight) from the measurement of the given parameter.

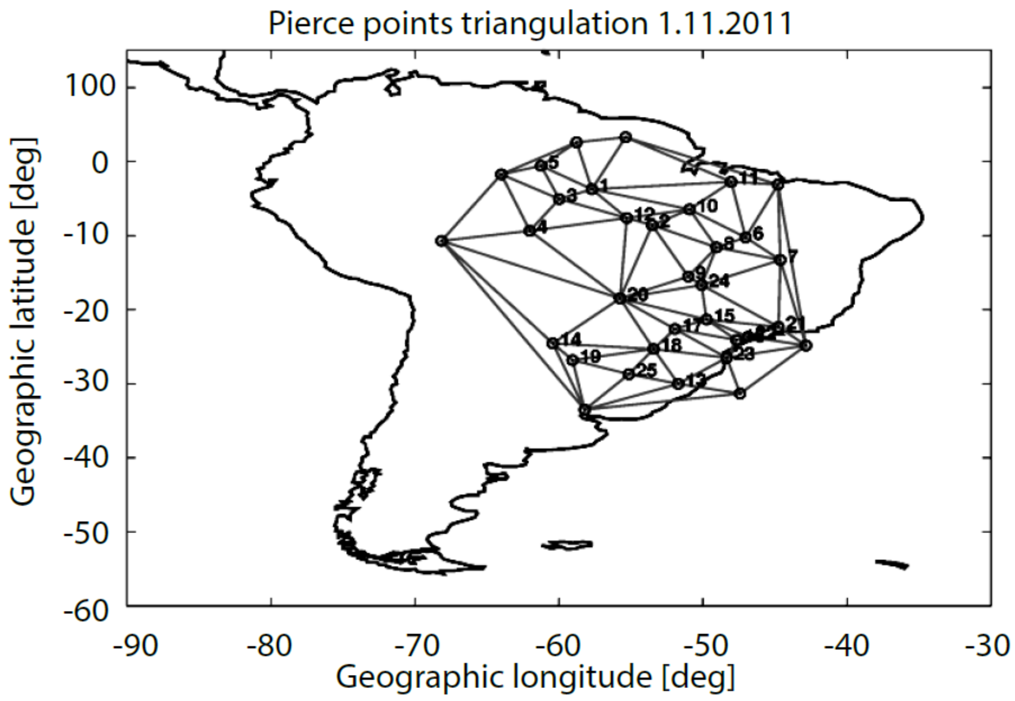
- The velocity field **v** is reconstructed by fitting it to the time changes of scalar field considered and then used to evolve the scalar field itself.

- Source term is necessary for scintillation parameters but not for TEC

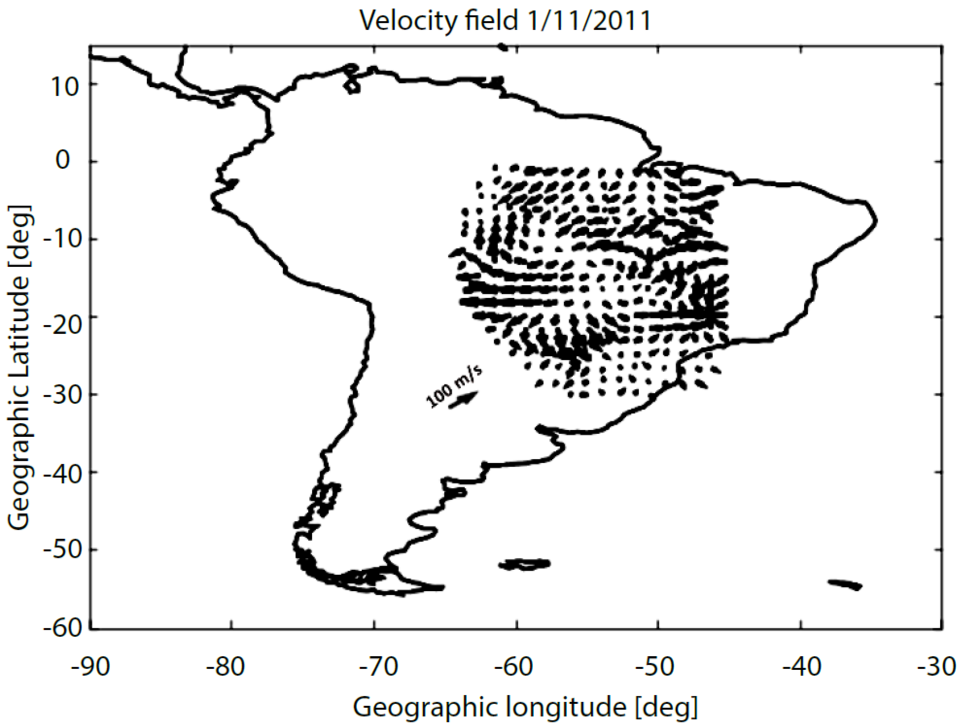
Model insights

The solution of the continuity equation relies on:

- discretizing the space with Delaunay triangulation
- approximating TEC and scintillation parameters piecewise linearly
- considering the velocity field constant over each triangle



Example of Delaunay triangulation



Example of reconstructed velocity field for TEC

Model performance

Model test TEC and scintillation parameters (S_4, σ_ϕ, p, T) data for five days under strong scintillation regime

PolaRxS
GPS + GLONASS
L1 frequency

Station ID	Location	Lat (°N)	Lon (°E)
PRU1	Presidente Prudente	-22.12	-51.41
PRU2	Presidente Prudente	-22.12	-51.40
PRU3	Presidente Prudente	-22.12	-51.41
GALH	Presidente Prudente	-22.12	-51.42
SJCU	San Jose dos Campos	-23.21	-45.96
SJCE	San Jose dos Campos	-23.21	-45.86
MAC2	Macaé	-22.38	-41.79

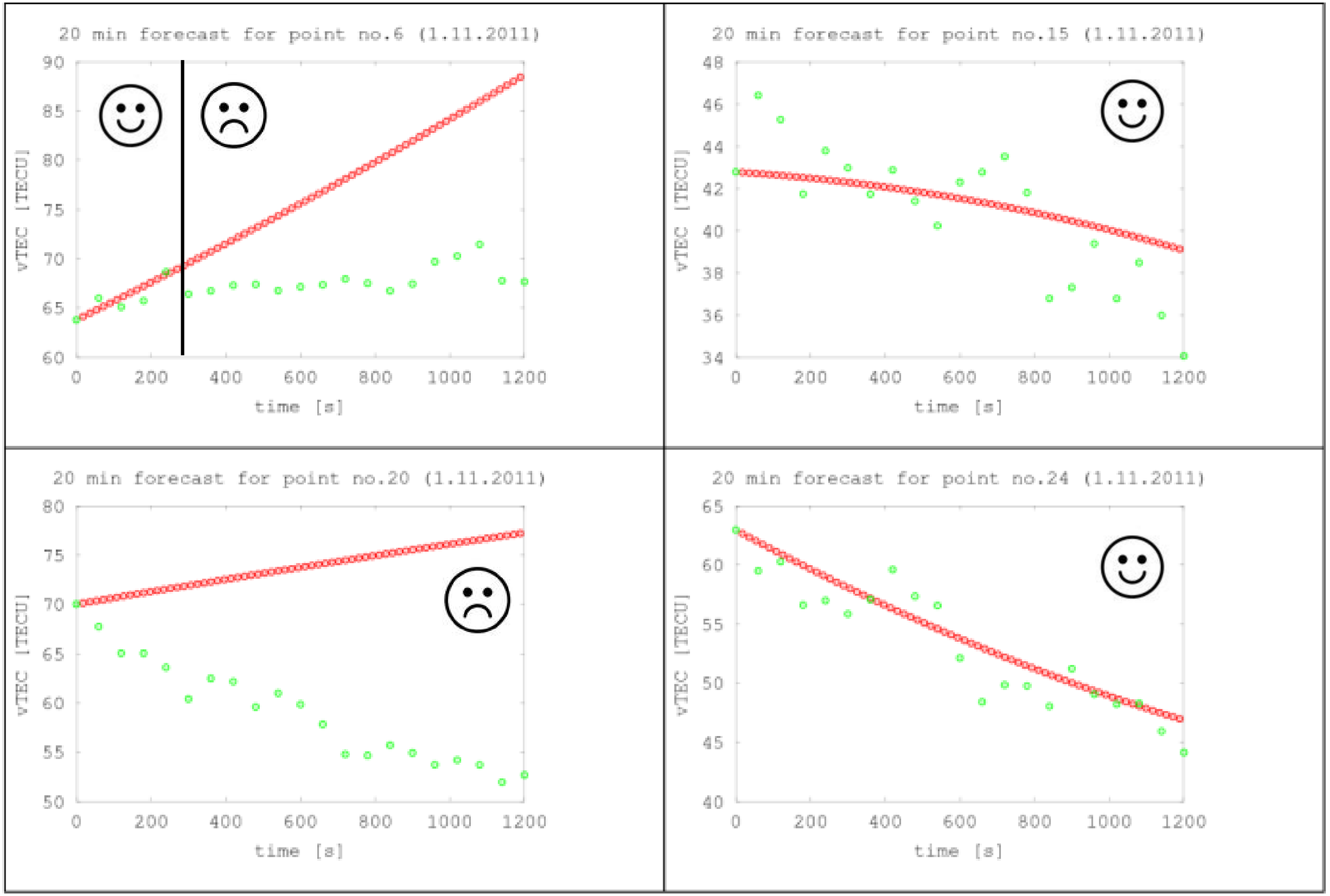
DAY	Input from:					
	PRU1	PRU2	PRU3	SJCU	SJCE	MAC2
269/2013	S	S	S			
271/2013	S	S	S		S	
338/2013		S	S	S		
340/2013		S	S	S	S	S
021/2014	S	S	S		S	

	full data
	about half data
	few data
	no data

S: strong scintillation (S4>0.7)

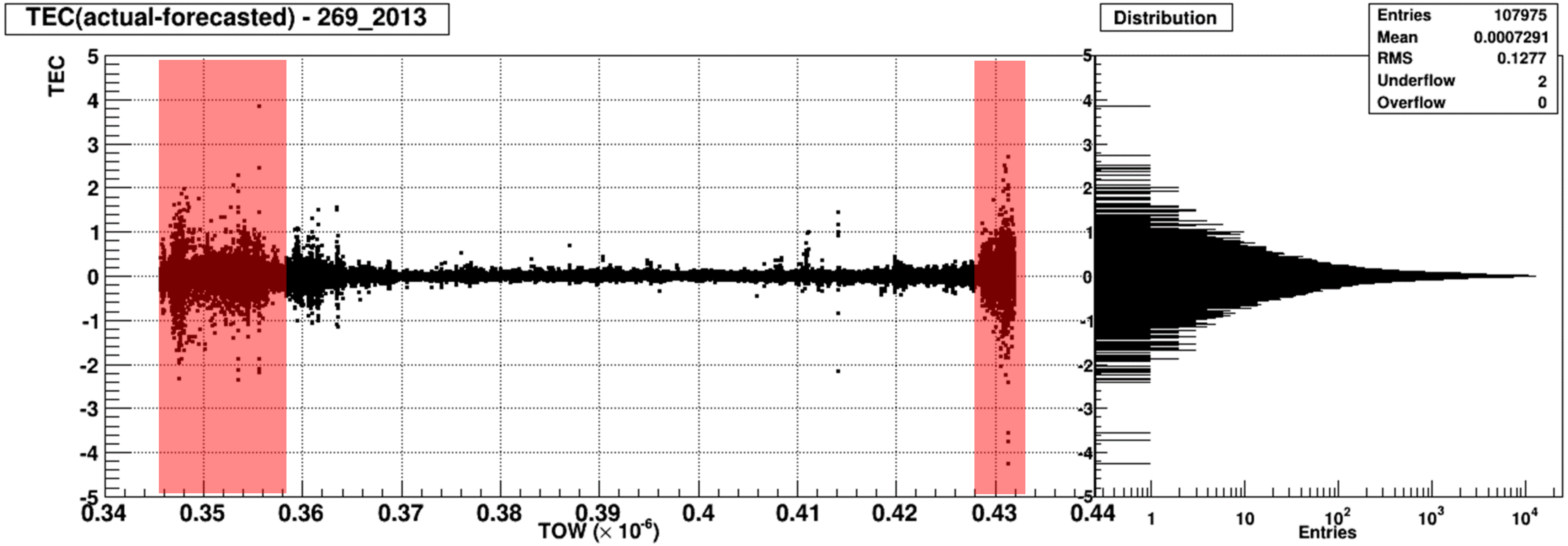
Model performance: comparison between different forecasting horizons

Day 11 November 2011



Comparison between **forecasted vTEC** and **actual vTEC** data vs. time for selected internal points.

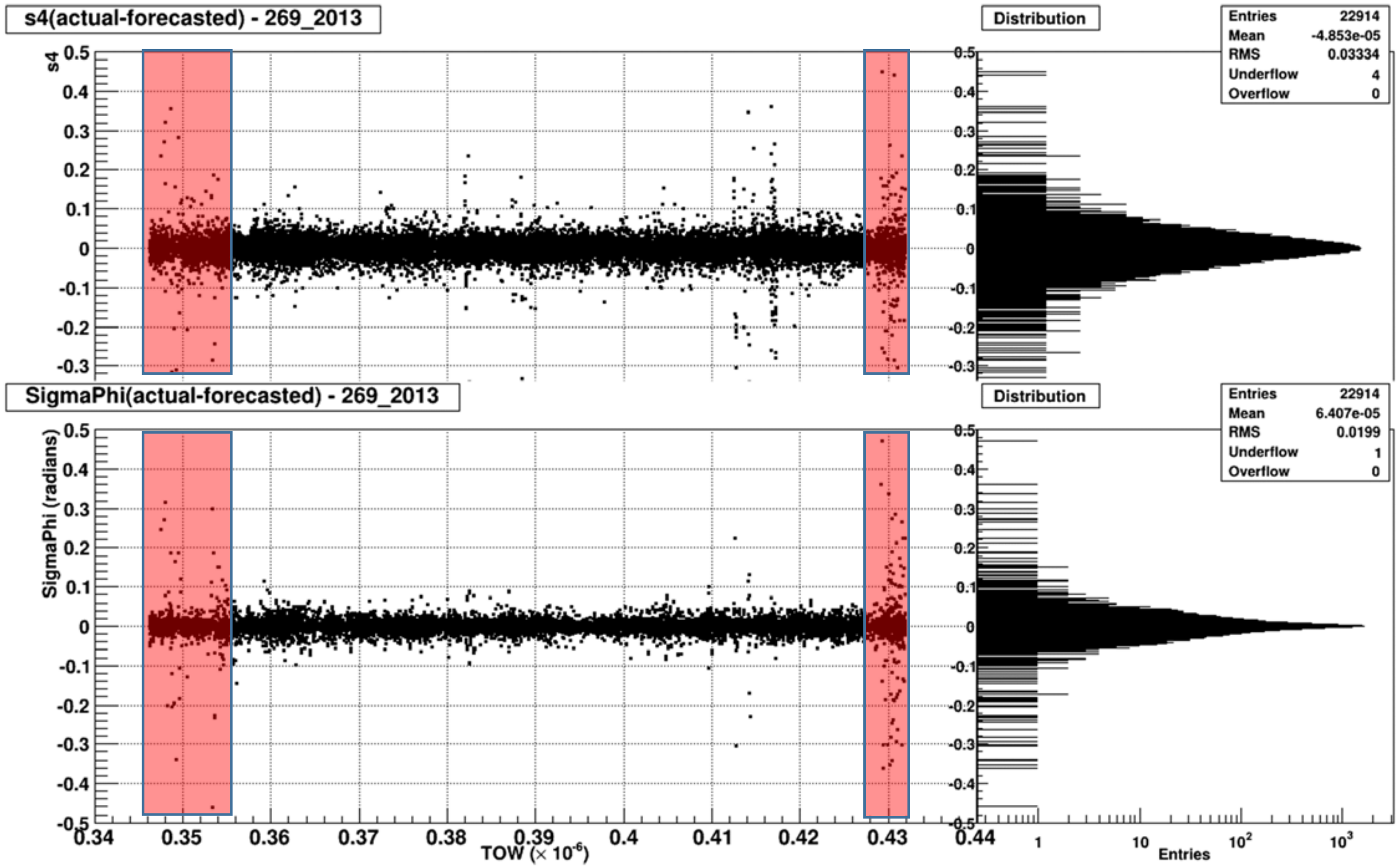
Model performance: vTEC
Day 269/2013 (26 September 2013)



- Differences between actual and forecasted TEC values
- Forecasting horizon: <u>15 seconds</u>
- The bulk of the distribution is between -1 and 1 TECu
- Prediction is harder during local post-sunset (red boxes)

Model performance: Scintillation parameters

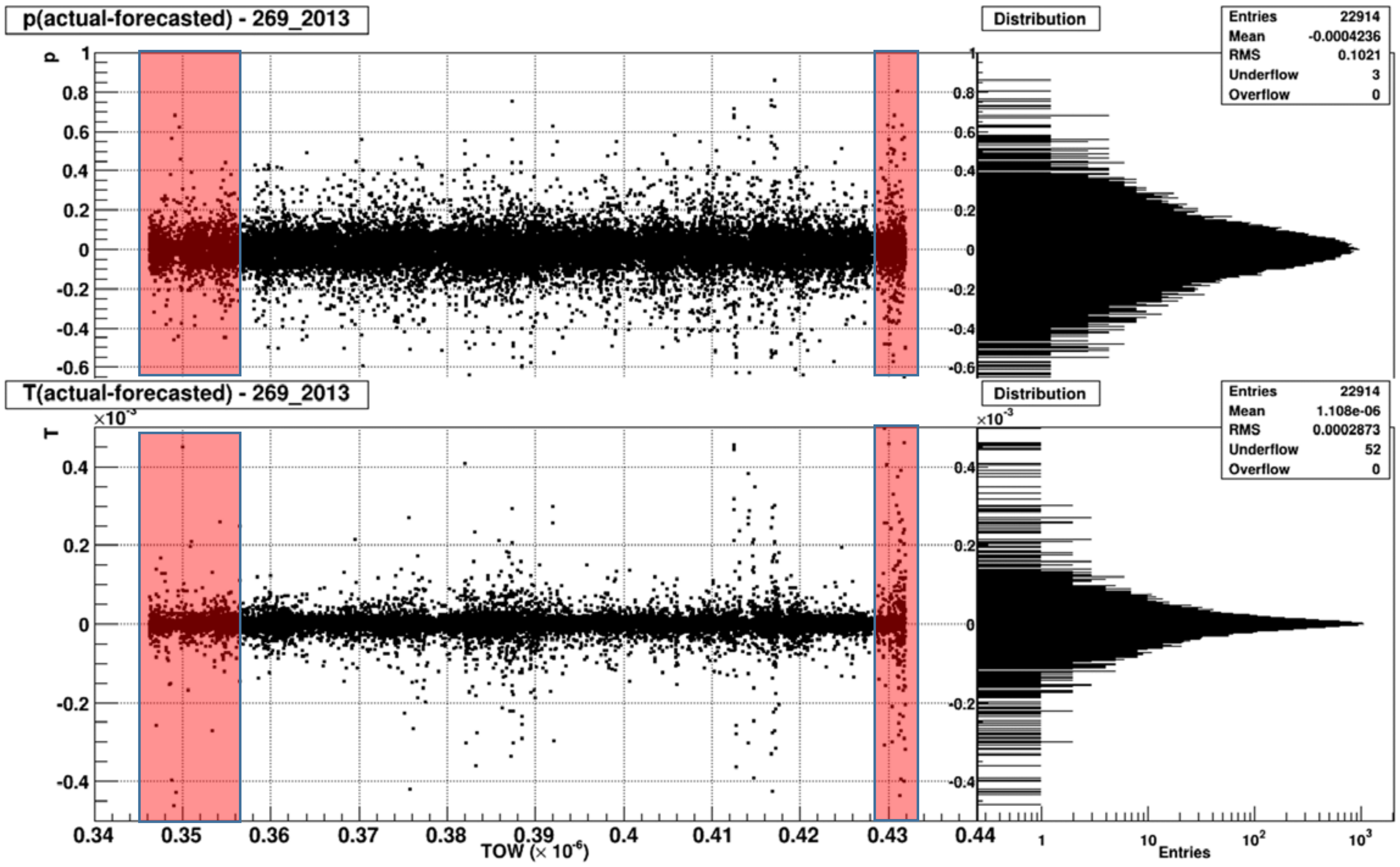
Day 269/2013 (26 September 2013)



- Differences between actual and forecasted S4 (top panel) and σ_Φ (bottom panel)
- Forecasting horizon: <u>1 minute</u>
- Differences range between -0.1 and 0.1 for both the parameters
- Prediction is harder during local post-sunset (red boxes)

Model performance: Scintillation parameters

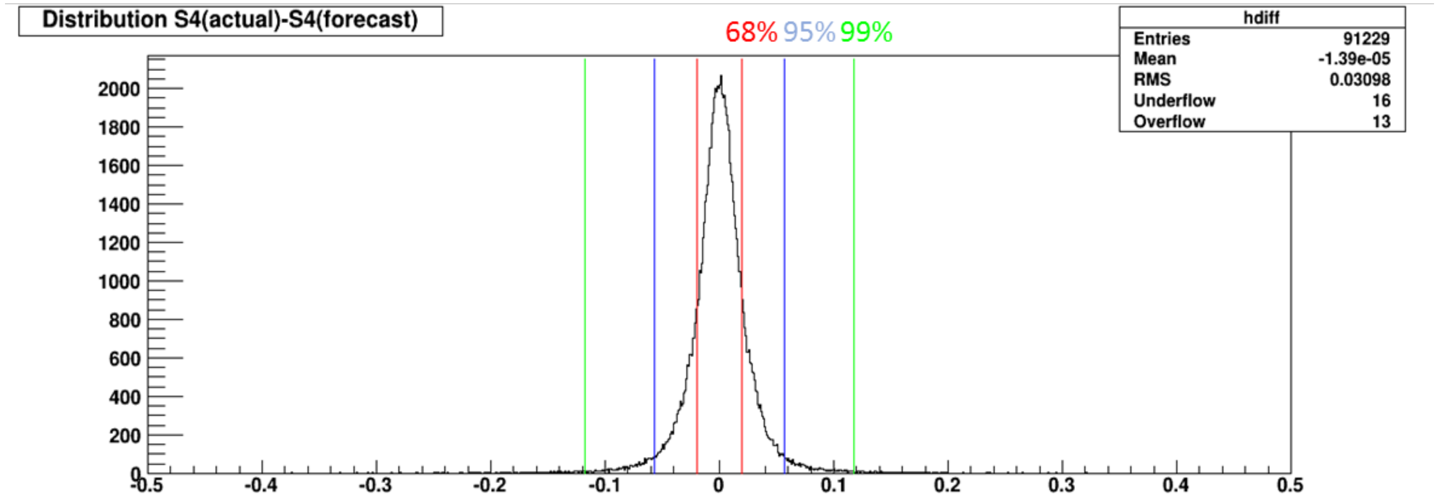
Day 269/2013 (26 September 2013)



- Differences between actual and forecasted p (top panel) and T (bottom panel)
- Forecasting horizon: 1 minute
- Differences range between -0.4 and 0.4 for p and between -0.05 and 0.05
- Errors on P seems to be indipendent from the scintillation regime

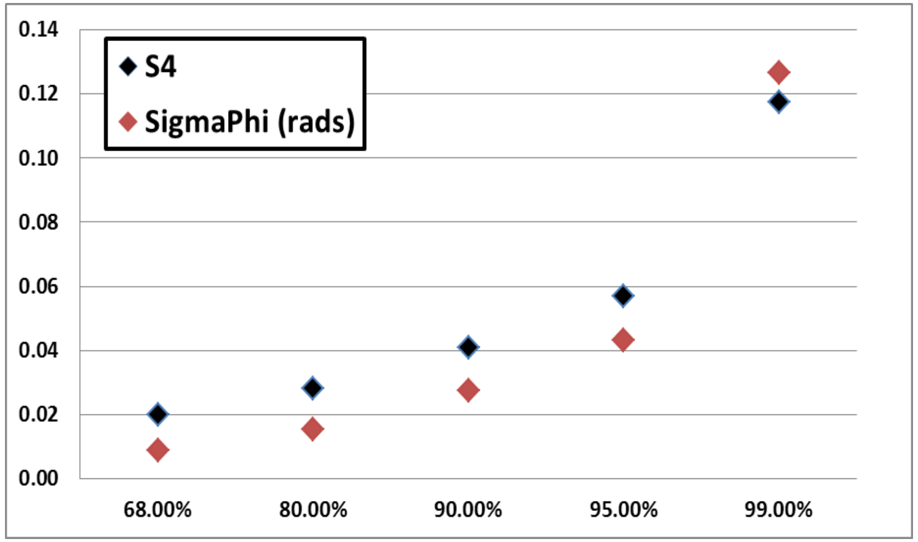
Model performance: overall resolution

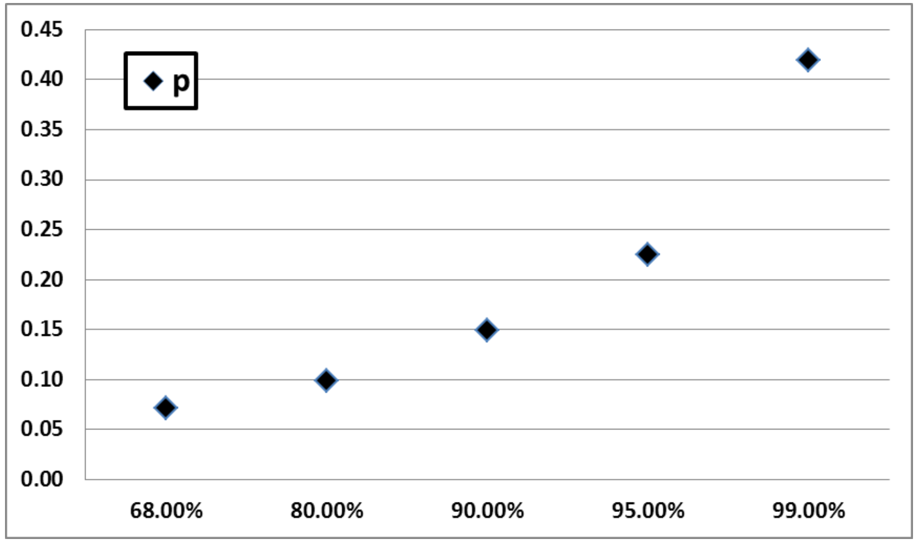
- Resolution is provided in terms of values of the tails at which the X% of the of distribution is included
- Various percentage have been evaluated
- Performance are suitable to support precision positioning algorithms
  - Example: TEC resultion is of the order of 1 TECu at 99%

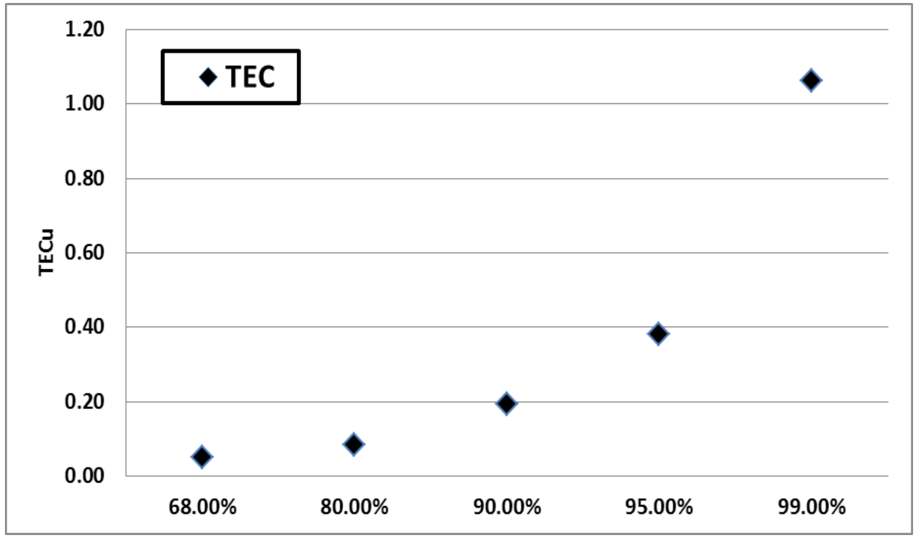


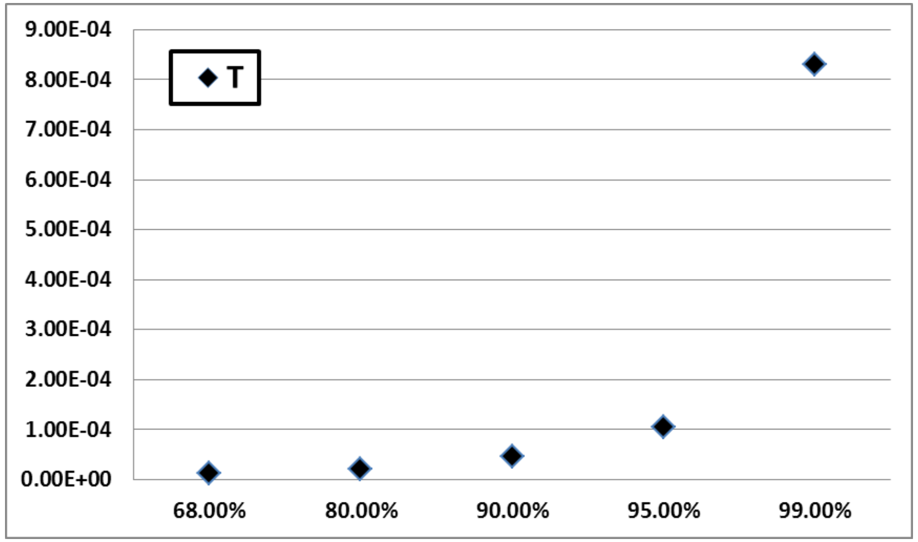
P	σ_{S4}	$\sigma_{\sigma\phi}$(rads)	σ_{TEC} (TECu)	σ_p	σ_T
68%	0.02	0.01	0.05	0.07	1.31E-05
80%	0.03	0.02	0.09	0.10	2.16E-05
90%	0.04	0.03	0.19	0.15	4.60E-05
95%	0.06	0.04	0.38	0.22	1.06E-04
99%	0.12	0.13	1.06	0.42	8.30E-04

Model performance: overall resolution



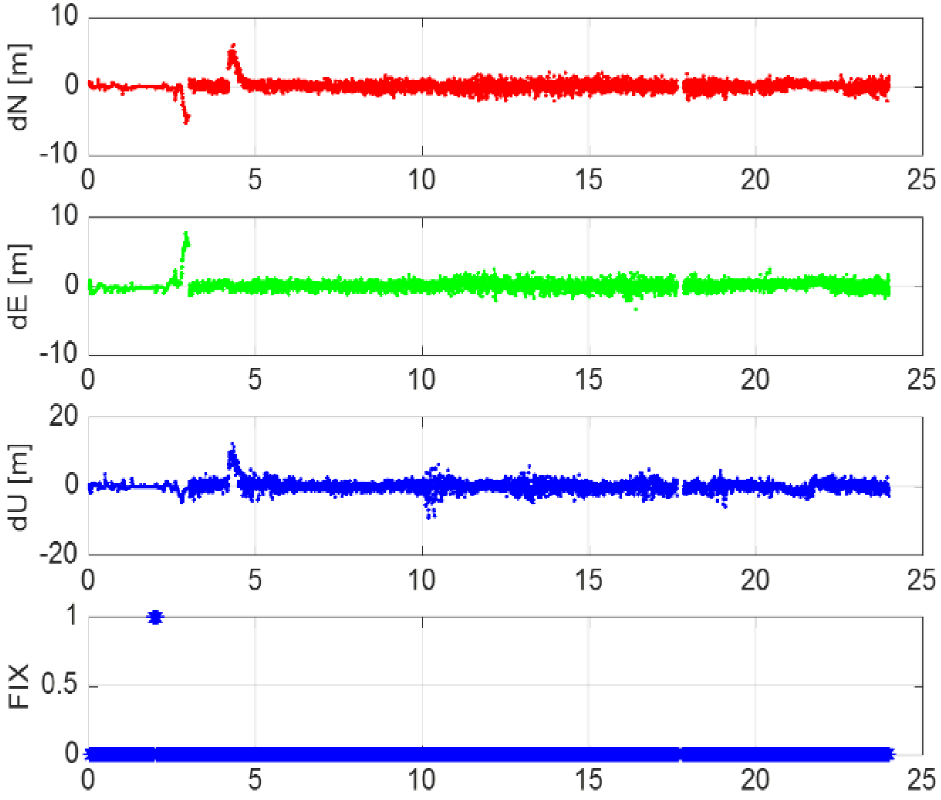


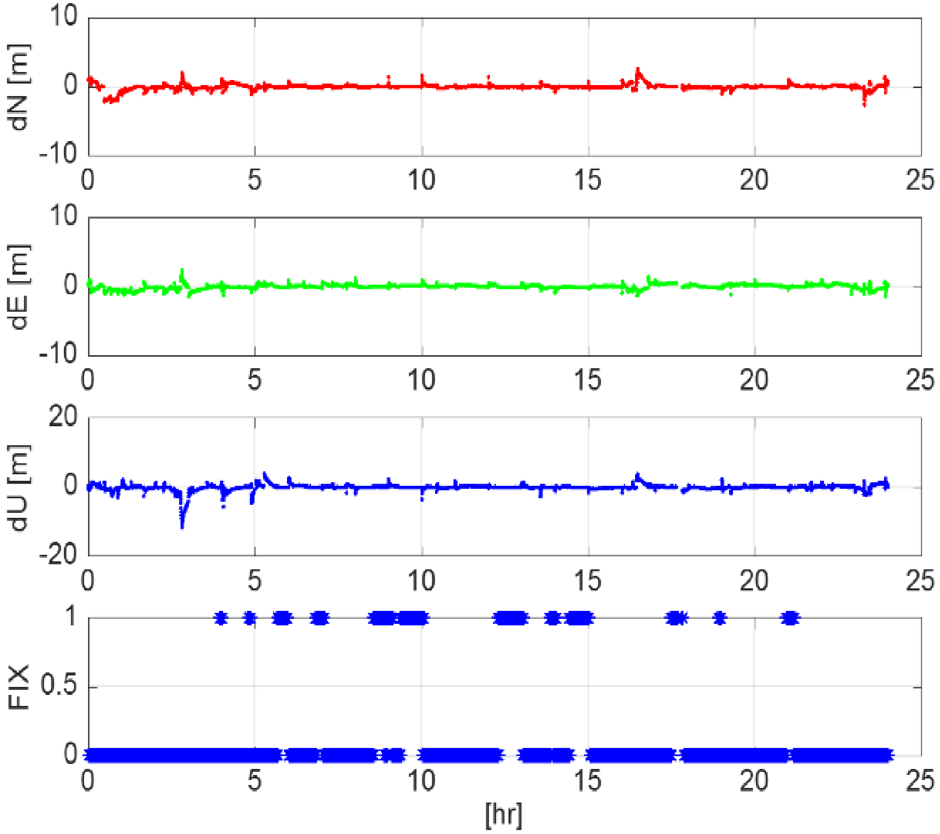




Model performance: mitigation on RTK

Positioning error analysis by applying external ionospheric information from GIM (left panel) and forecasted TEC maps (rigth). Plots refer to a long baseline (about 120 km) between São José de Rio Preto and Araçatuba during 19 March 2015.





The AR success rate for the GIM and forecasted TEC map are 0.4% and 15.9% respectively, while the 3D positioning RMSs including both float and fixed solutions are 1.341 m and 0.608 m.

Concluding remarks

- A empirical regional short-term forecasting model has been recently developed and patented.
- The model relies on suitable networks of GNSS receivers
- The model is able to provide TEC and scintillation parameters (if provided by the receivers) from seconds to minutes in advance
- Model tests have been conducted in the frame of CALIBRA project over Brazil and under strong scintillation conditions
- The overall forecasting performance are good, based on the errors associated to the forecasted values of TEC and scintillation parameters
- Model is ready to be tuned and included in firmware to support NRTK applications

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Thank You!

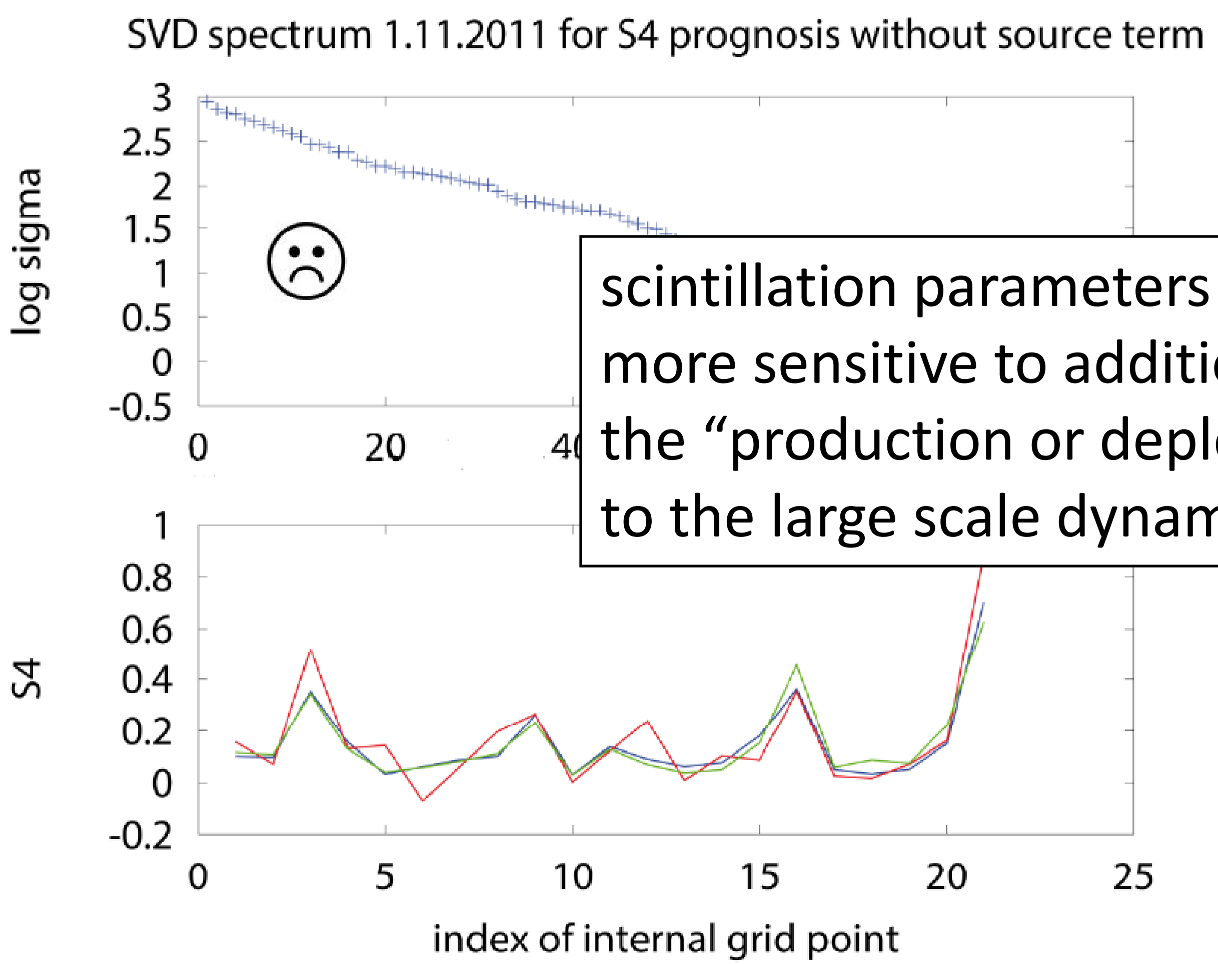
Bacup slides

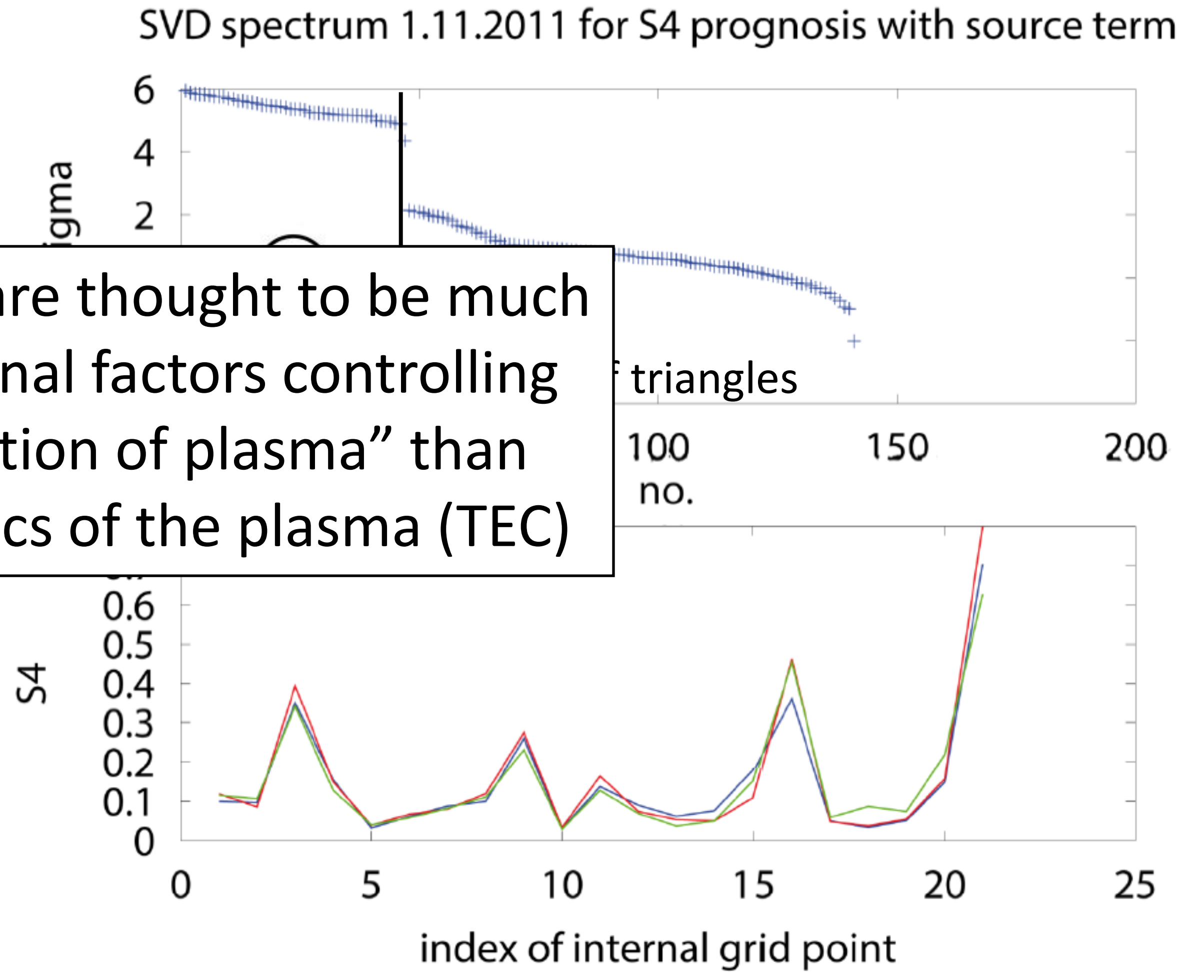
Model results: Summary

DAY	(actual - predicted) standard deviation				
	S4	**SigmaPhi**	**TEC**	**p**	**T**
269/2013	0.033	0.020	0.13	0.10	2.87E-04
271/2013	0.031	0.032	0.81	0.11	4.84E-04
338/2013	0.036	0.037	0.40	0.34	4.57E-04
340/2013	0.033	0.042	0.34	0.12	6.28E-04
021/2014	0.030	0.059	0.64	0.11	3.70E-04

P	σ_{S4}	$\sigma_{\sigma\phi}$(rads)	σ_{TEC} (TECu)	σ_p	σ_T
68%	0.02	0.01	0.05	0.07	1.31E-05
80%	0.03	0.02	0.09	0.10	2.16E-05
90%	0.04	0.03	0.19	0.15	4.60E-05
95%	0.06	0.04	0.38	0.22	1.06E-04
99%	0.12	0.13	1.06	0.42	8.30E-04

The empirical reason why scintillation parameters need the source term





scintillation parameters are thought to be much more sensitive to additional factors controlling the "production or depletion of plasma" than to the large scale dynamics of the plasma (TEC)

Blue line represents initial condition at T0, green line the actual values at T0+1 min, and the red one 1min forecasted values at T0+1min.