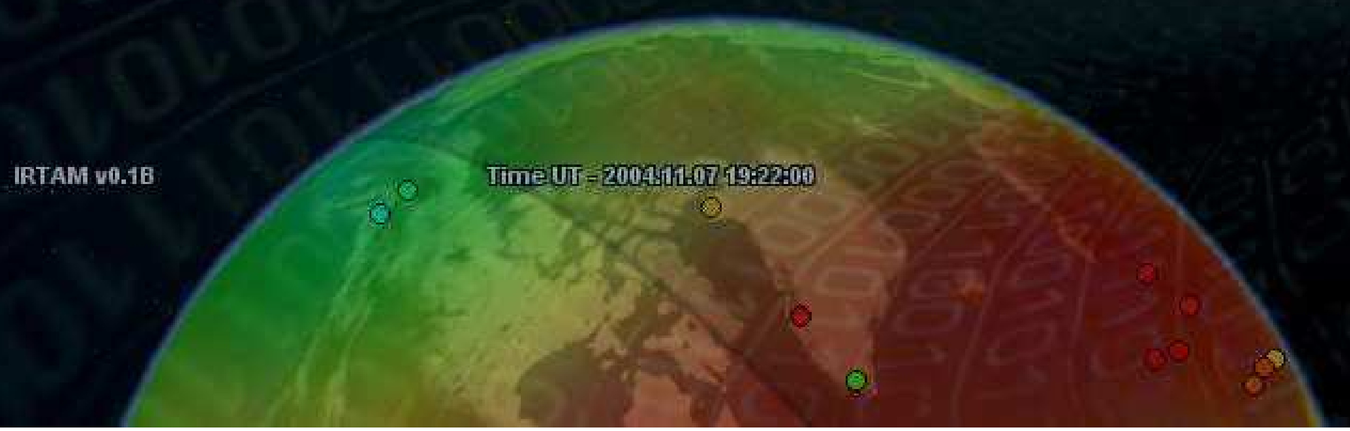
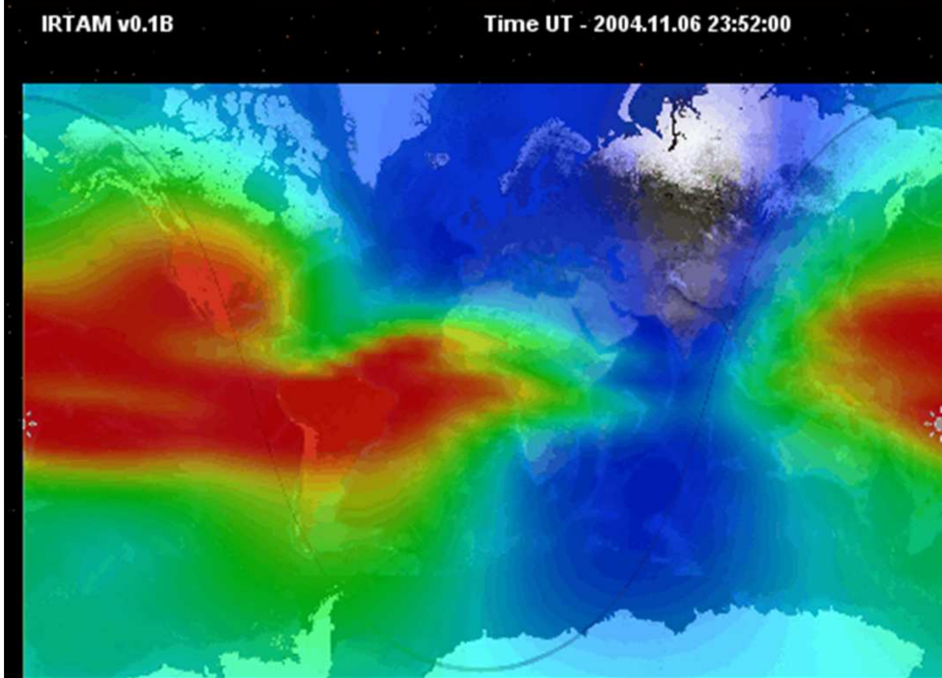
Real-Time IRI Driven by GIRO Data

Ivan Galkin, Bodo Reinisch, Xueqin Huang, Dieter Bilitza, and Artem Vesnin

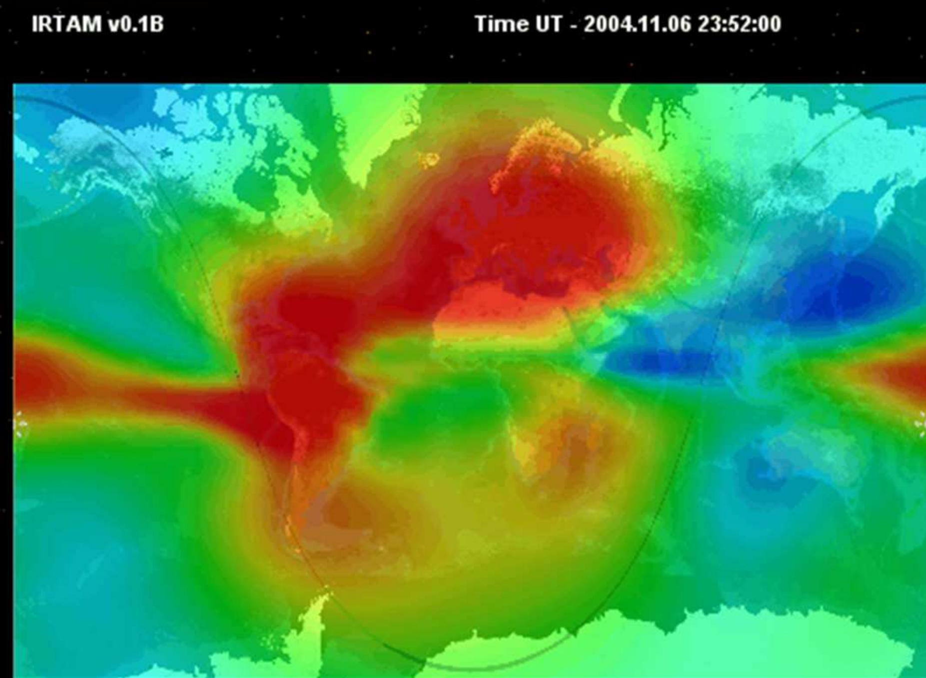
University of Massachusetts Lowell / Center for Atmospheric Research / Physics Department
Lowell Digisonde International, LLC
George Mason University, Space Weather Laboratory
Heliophysics Laboratory, NASA Goddard Space Flight Center

Real-Time-IRI Task Force Meeting ● Lowell, MA ● May 19, 2014





Peak density (foF2)



Peak height (hmF2)

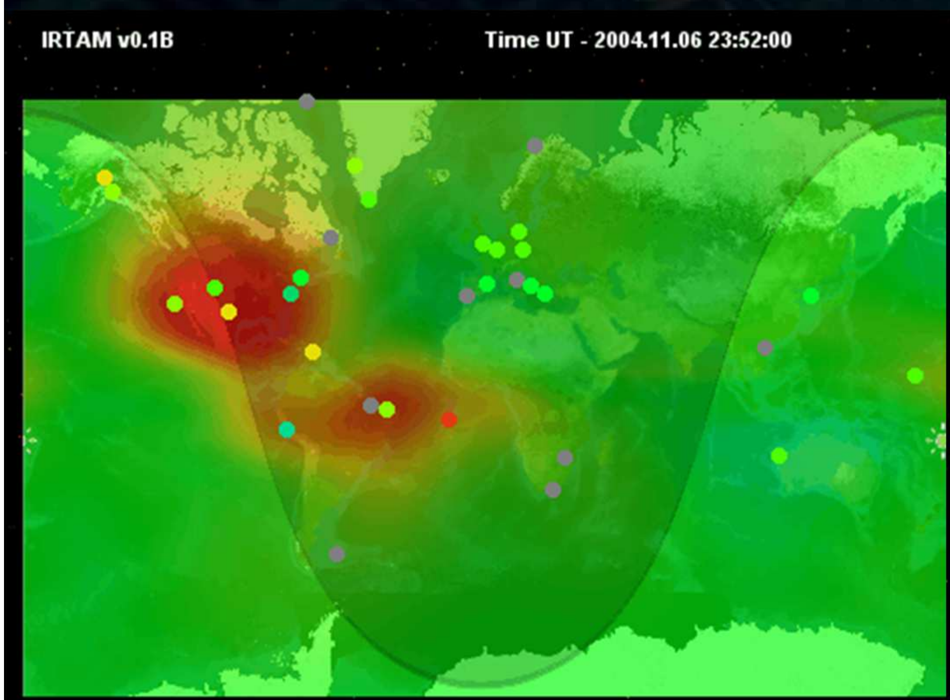
Real-Time Fusion of IRI model and GIRO observations

NECTAR

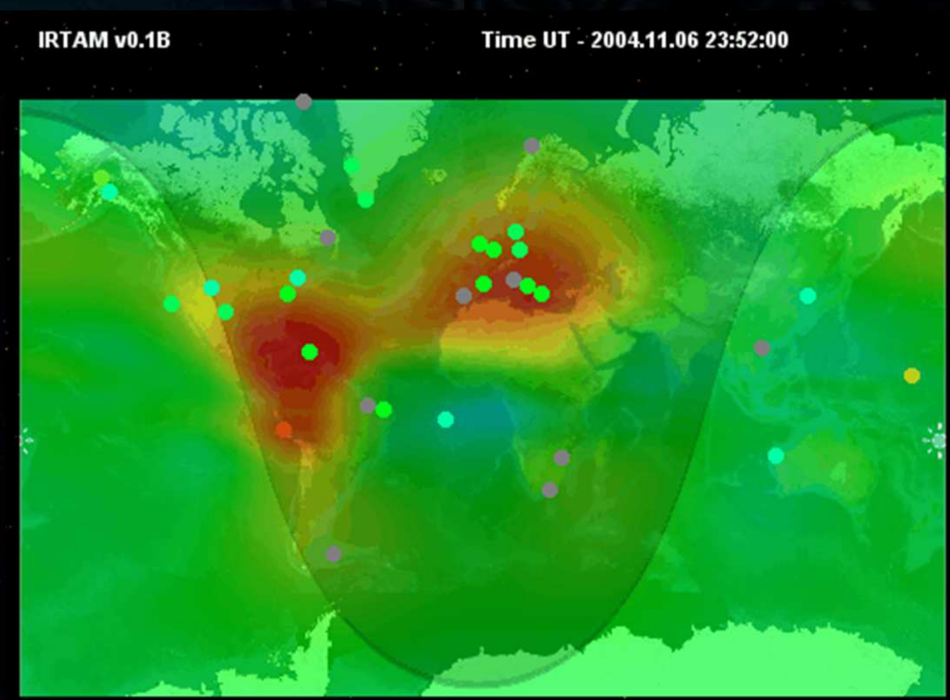
http://giro.uml.edu/IRTAM

IRTAM v0.1B Time UT - 2004.11.07 19:22:00

American National Standard (AIAA, 2011) listed 46 ionospheric models



Peak density deviation (ΔfoF2)



Peak height deviation (ΔhmF2)

Real-Time Deviation of F2 Peak from Expected Climatology

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http://giro.uml.edu/IRTAM

American National Standard (AIAA, 2011) listed 46 ionospheric models

Jones-Garret Expansion for foF2 maps in IRI

Time · Latitude · Longitude · Coefficients · Expansion Base Functions

$$foF2(t,\lambda,\theta) = \sum_i \sum_n \sum_m C_{inm} F_{inm}(t,\lambda,\theta)$$

Time · Latitude · Longitude

Diurnal expansion – classic Temporal Harmonics of 6th degree (13 coefficients)
Spatial expansion – highly customized Geographic functions Gk (76 coefficients)

Assimilation Design: produce new coefficients; keep classic base functions

76 Gk base functions

Classic Longitudinal Harmonics 8^{th} order

$$G_k = \Big(\overbrace{\sin^n \chi}^{\text{B-field factor}}\Big)\cdot\Big(\overbrace{\cos^m \lambda}^{\text{Pole suppressor}}\Big)\cdot\begin{bmatrix}\cos m\theta \\ \sin m\theta\end{bmatrix}$$

modip

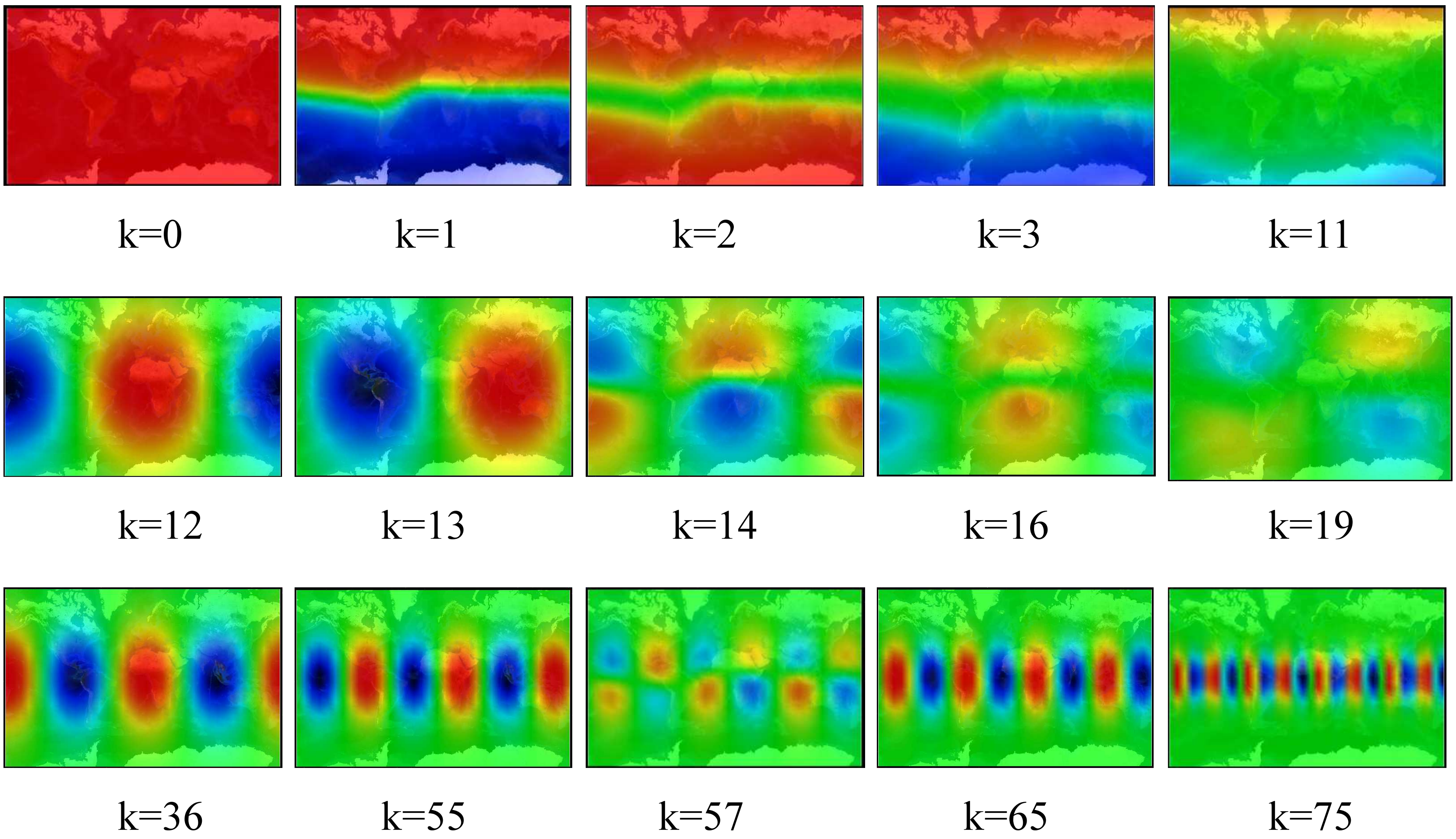
$$\chi(\lambda,\theta) = \arctan\frac{I(\lambda,\theta)}{\sqrt{\cos\theta}}$$

$$m = 0..8$$

$$n(m) = \{11, 11, 8, 4, 1, 0, 0, 0, 0\}$$

0	1	n=0..11 m=0
1	$\sin x$	
2	$\sin^2 x$	
3	$\sin^3 x$	
4	$\sin^4 x$	
5	$\sin^5 x$	
6	$\sin^6 x$	
7	$\sin^7 x$	
8	$\sin^8 x$	
9	$\sin^9 x$	
10	$\sin^{10} x$	
11	$\sin^{11} x$	
12	$\cos\lambda\ \cos\theta$	n=0..11 m=1
13	$\cos\lambda\ \sin\theta$	
14	$\sin x\ \cos\lambda\ \cos\theta$	
15	$\sin x\ \cos\lambda\ \sin\theta$	
16	$\sin^2 x\ \cos\lambda\ \cos\theta$	
17	$\sin^2 x\ \cos\lambda\ \sin\theta$	
18	$\sin^3 x\ \cos\lambda\ \cos\theta$	
19	$\sin^3 x\ \cos\lambda\ \sin\theta$	
20	$\sin^4 x\ \cos\lambda\ \cos\theta$	
21	$\sin^4 x\ \cos\lambda\ \sin\theta$	
22	$\sin^5 x\ \cos\lambda\ \cos\theta$	
23	$\sin^5 x\ \cos\lambda\ \sin\theta$	
24	$\sin^6 x\ \cos\lambda\ \cos\theta$	
25	$\sin^6 x\ \cos$ [illegible]	
26	$\sin^7 x\ \cos$ [illegible]	
27	$\sin^7 x\ \cos$ [illegible]	
28	$\sin^8 x\ \cos\lambda\ \cos\theta$	
29	$\sin^8 x\ \cos\lambda\ \sin\theta$	
30	$\sin^9 x\ \cos\lambda\ \cos\theta$	
31	$\sin^9 x\ \cos\lambda\ \sin\theta$	
32	$\sin^{10} x\ \cos\lambda\ \cos\theta$	
33	$\sin^{10} x\ \cos\lambda\ \sin\theta$	
34	$\sin^{11} x\ \cos\lambda\ \cos\theta$	
35	$\sin^{11} x\ \cos\lambda\ \sin\theta$	
36	$\cos^2\lambda\ \cos 2\theta$	n=0..8 m=2
37	$\cos^2$ [illegible]	
38	$\sin x\ \cos^2$ [illegible]	
39	$\sin x\ \cos^2$ [illegible]	
40	$\sin^2 x\ \cos^2\lambda\ \cos 2\theta$	
41	$\sin^2 x\ \cos^2\lambda\ \sin 2\theta$	
42	$\sin^3 x\ \cos^2\lambda\ \cos 2\theta$	
43	$\sin^3 x\ \cos^2\lambda\ \sin 2\theta$	
44	$\sin^4 x\ \cos^2\lambda\ \cos 2\theta$	
45	$\sin^4 x\ \cos^2\lambda\ \sin 2\theta$	
46	$\sin^5 x\ \cos^2\lambda\ \cos 2\theta$	
47	$\sin^5 x\ \cos^2\lambda\ \sin 2\theta$	
48	$\sin^6 x\ \cos^2\lambda\ \cos 2\theta$	
49	$\sin^6 x\ \cos^2\lambda\ \sin 2\theta$	
50	$\sin^7 x\ \cos^2\lambda\ \cos 2\theta$	
51	$\sin^7 x\ \cos^2\lambda\ \sin 2\theta$	
52	$\sin^8 x\ \cos^2\lambda\ \cos 2\theta$	
53	$\sin^8 x\ \cos^2\lambda\ \sin 2\theta$	
54	$\cos^3\lambda\ \cos 3\theta$	n=0..4 m=3
55	$\cos^3\lambda\ \sin 3\theta$	
56	$\sin x\ \cos^3\lambda\ \cos 3\theta$	
57	$\sin x\ \cos^3\lambda\ \sin 3\theta$	
58	$\sin^2 x$ [illegible] 3θ	
59	$\sin^2 x$ [illegible] 3θ	
60	$\sin^3 x$ [illegible] 3θ	
61	$\sin^3 x\ \cos^3\lambda\ \sin 3\theta$	
62	$\sin^4 x\ \cos^3\lambda\ \cos 3\theta$	
63	$\sin^4 x\ \cos^3\lambda\ \sin 3\theta$	
64	co [illegible] 4θ	n=0..1 m=4
65	co [illegible] 4θ	
66	$\sin x$ co [illegible] 4θ	
67	$\sin x$ co [illegible] 4θ	
68	$\cos^5\lambda\ \cos 5\theta$	
69	$\cos^5\lambda\ \sin 5\theta$	
70	$\cos^6\lambda\ \cos 6\theta$	
71	$\cos^6\lambda\ \sin 6\theta$	
72	$\cos^7\lambda\ \cos 7\theta$	
73	$\cos^7\lambda\ \sin 7\theta$	
74	$\cos^8\lambda\ \cos 8\theta$	
75	$\cos^8\lambda\ \sin 8\theta$	

Spatial base function examples



Real-Time Measurements by GIRO

Problem is overdetermined in time domain and underdetermined in space domain

IRTAM Approach One

1. Overdetermined task in time: obtain 13 coefficients from 96 data points at each GIRO observatory location

Excessive data points can be used for quality control

2. Underdetermined task in space: obtain 76 coefficients from 40+ data locations

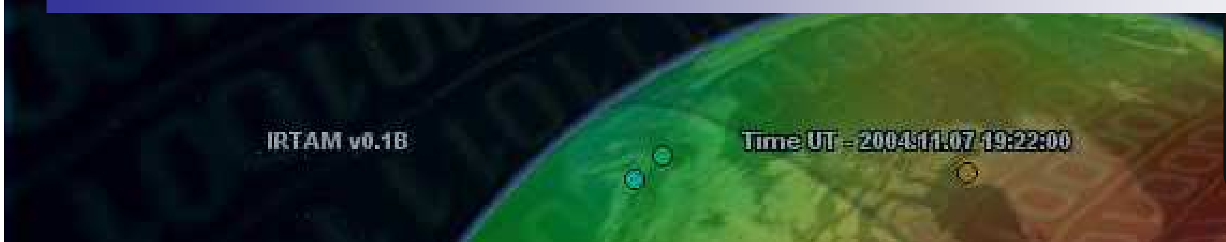
Certain interpolation rules are needed

Interpolation Ideas

Currently implemented two-step procedure: (a) time domain, (b) space domain

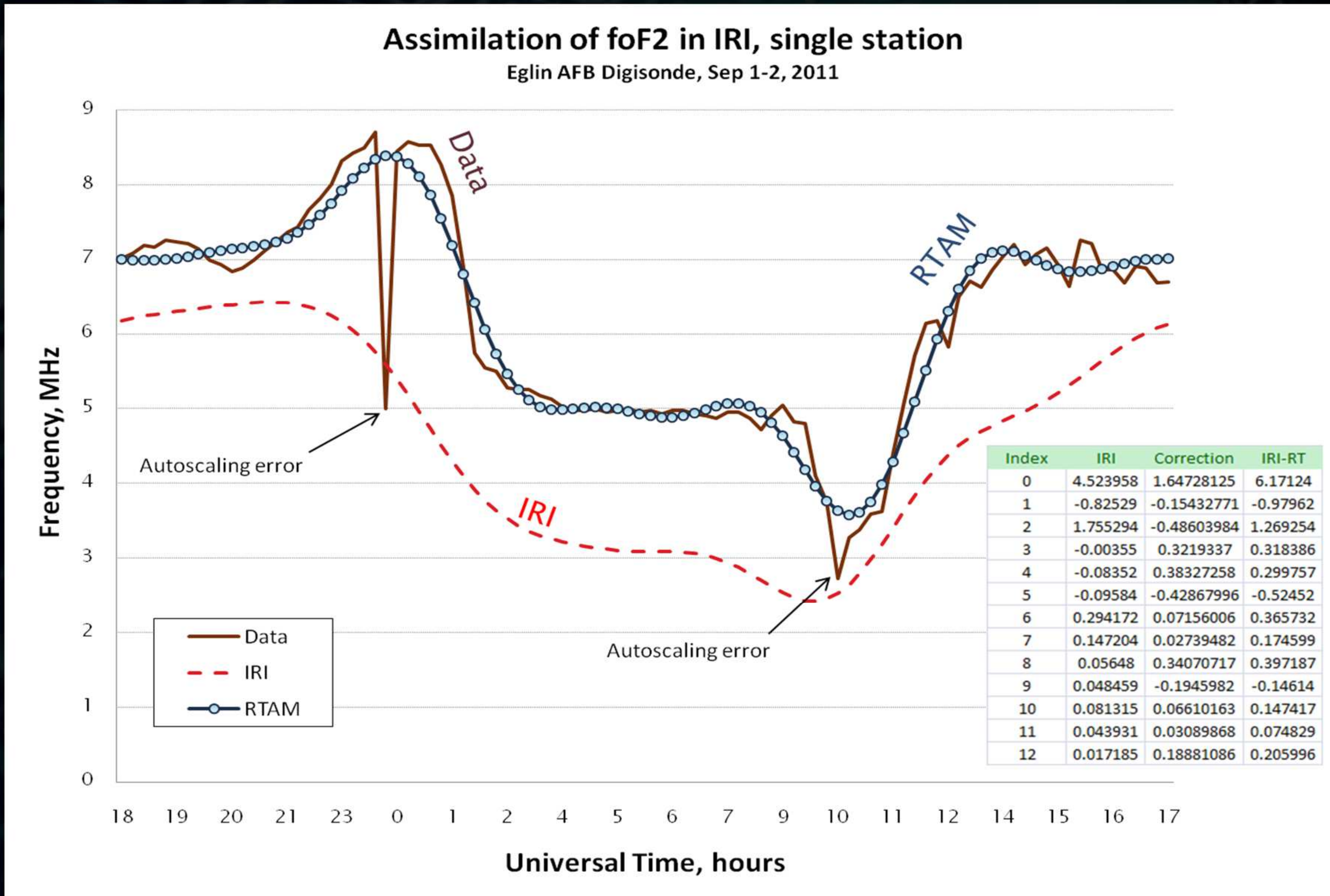
1. Compute 96 “data-model” deviations in time domain Δ_m
2. Expand 96 deviations Δ_m in 13 coefficients ΔC_i
3. Expand each ΔC_i in 76 coefficients ΔC_{ik}

$$C_{ik}^{*} = C_{ik} + \Delta C_{ik}$$

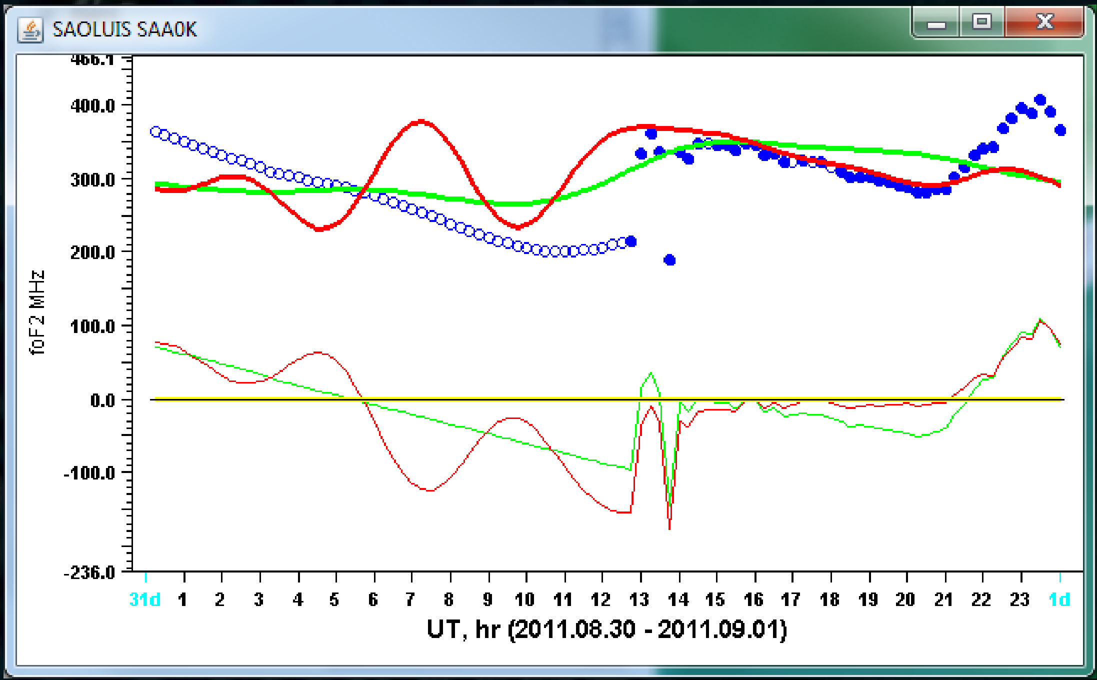


Direct computation of global 24-hour error compensation term

Robustness to Autoscaling Errors



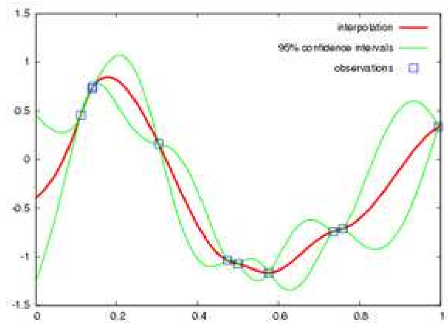
Index	IRI	Correction	IRI-RT
0	4.523958	1.64728125	6.17124
1	-0.82529	-0.15432771	-0.97962
2	1.755294	-0.48603984	1.269254
3	-0.00355	0.3219337	0.318386
4	-0.08352	0.38327258	0.299757
5	-0.09584	-0.42867996	-0.52452
6	0.294172	0.07156006	0.365732
7	0.147204	0.02739482	0.174599
8	0.05648	0.34070717	0.397187
9	0.048459	-0.1945982	-0.14614
10	0.081315	0.06610163	0.147417
11	0.043931	0.03089868	0.074829
12	0.017185	0.18881086	0.205996



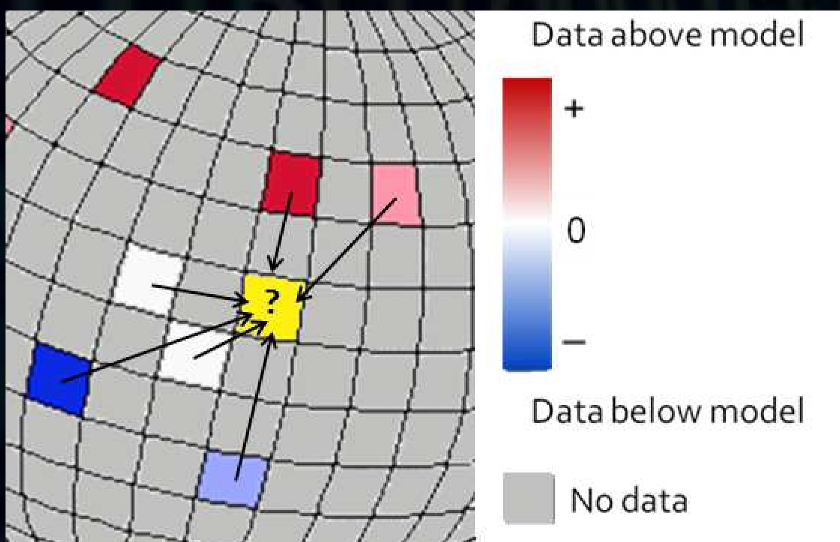
How “bad” is interpolation?

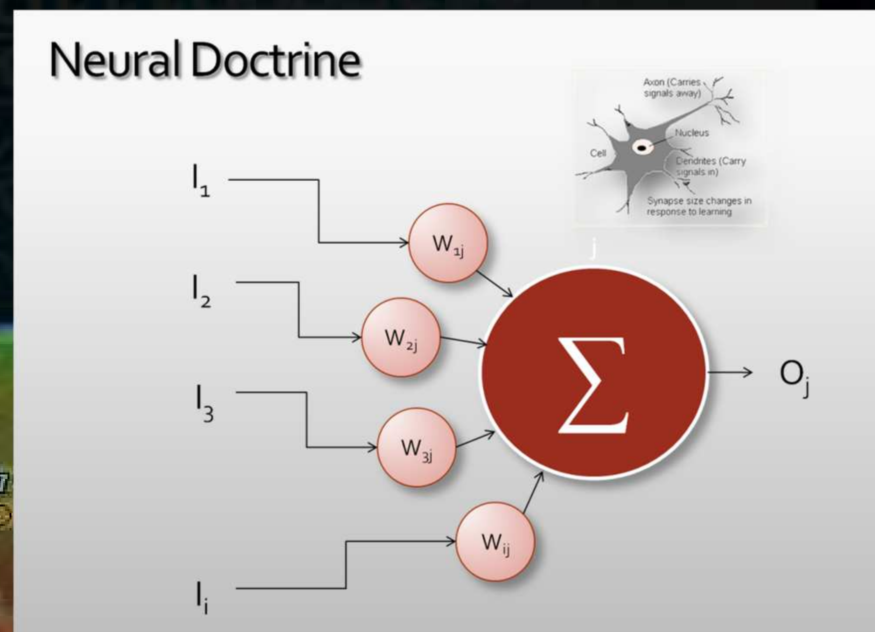
1. It is not foF2 that is interpolated
2. It is not ΔfoF2 that is interpolated
3. Each of 13 ΔC_i is interpolated individually

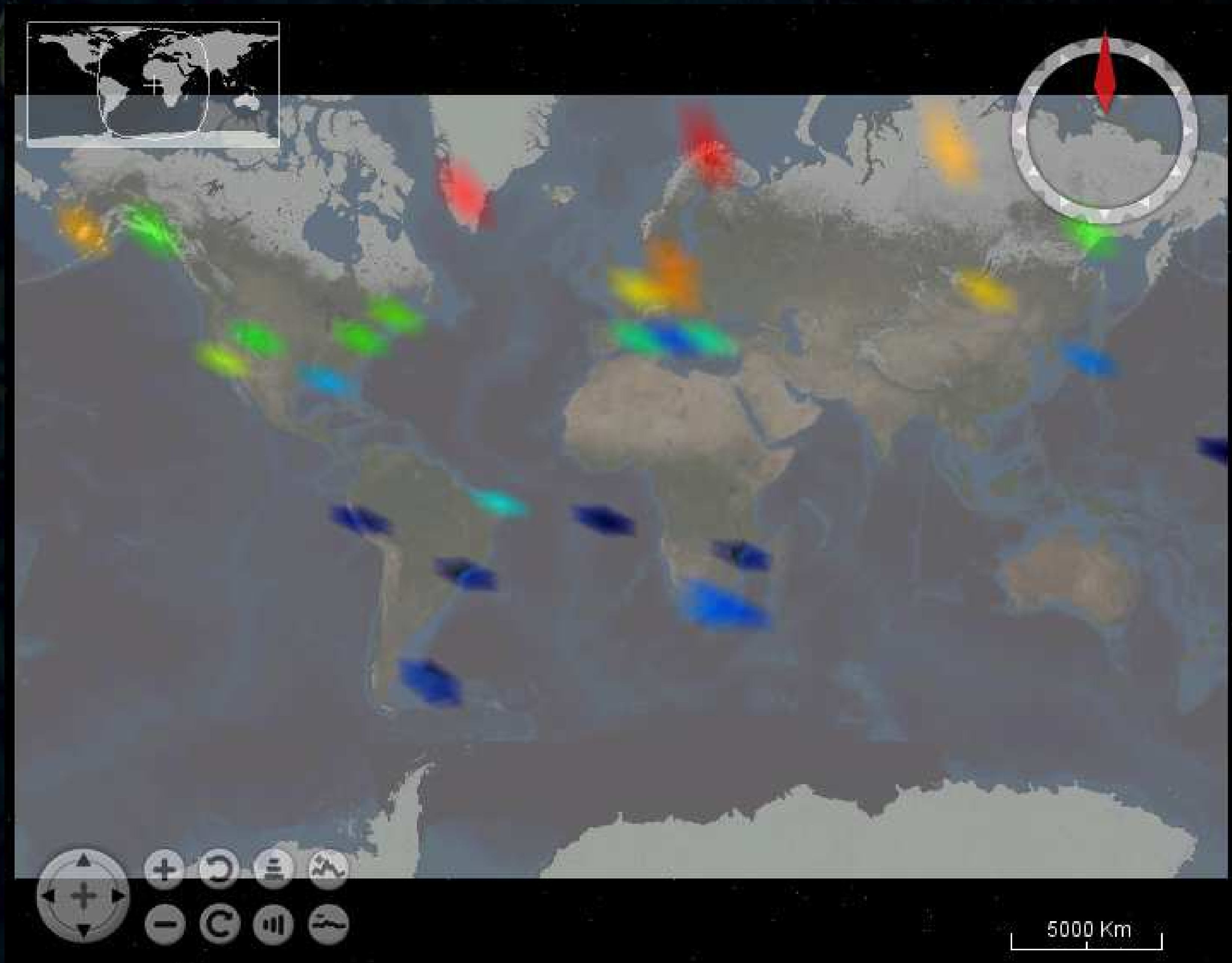
Compare to Kriging

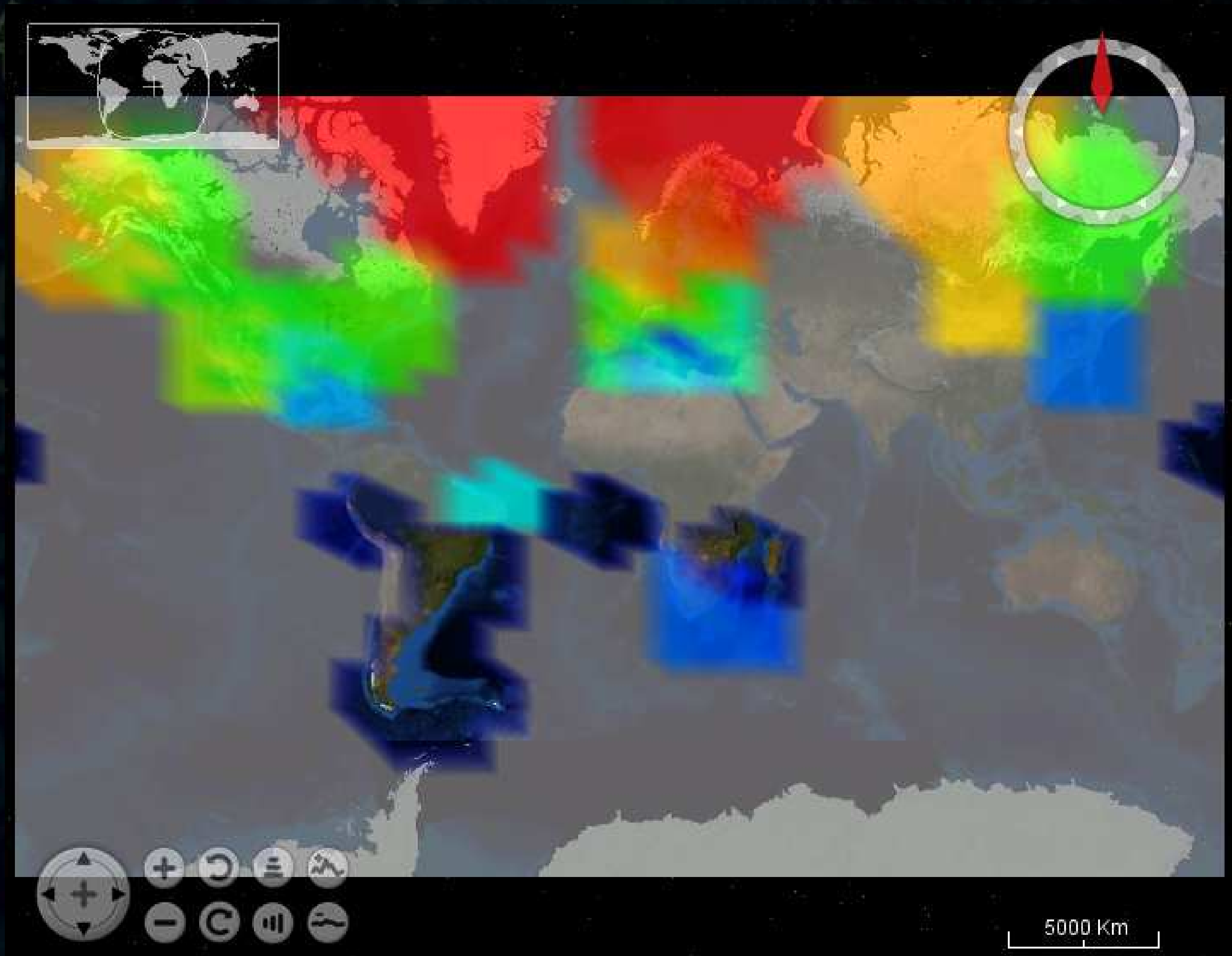


- Linear least squares estimate
- Predictor function has to be assumed
- Least squares minimize error of predictor at known points






5000 Km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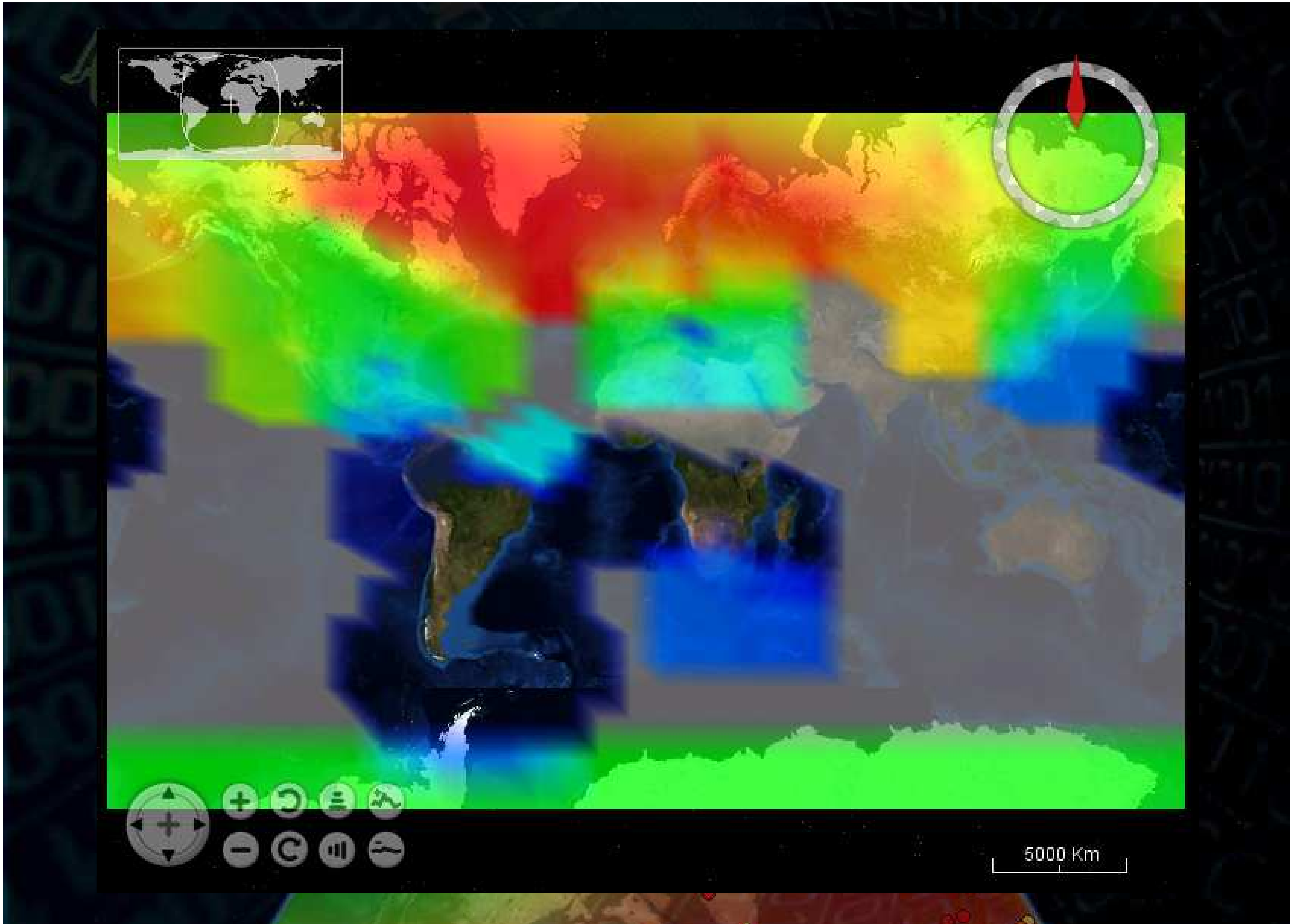
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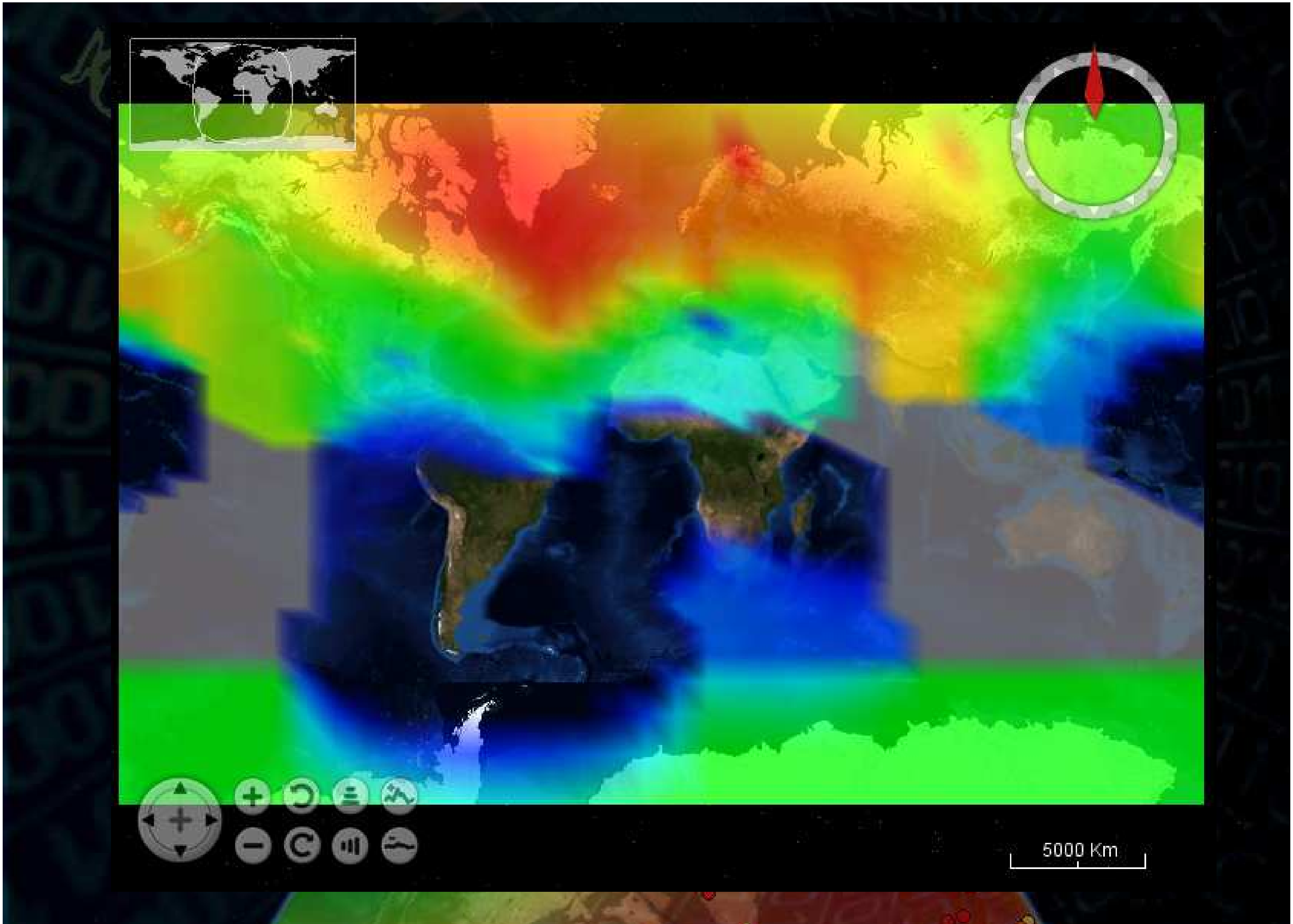
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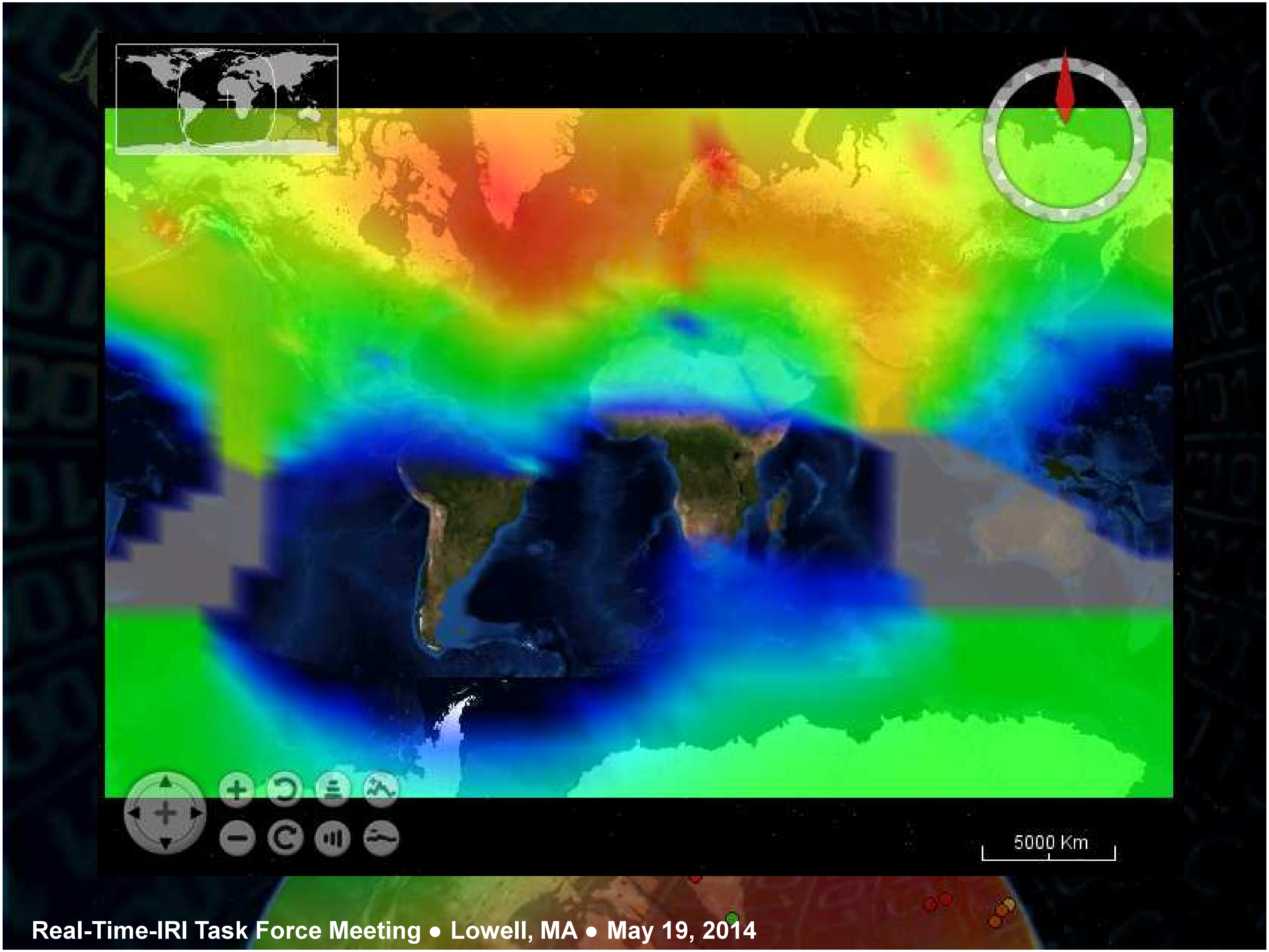
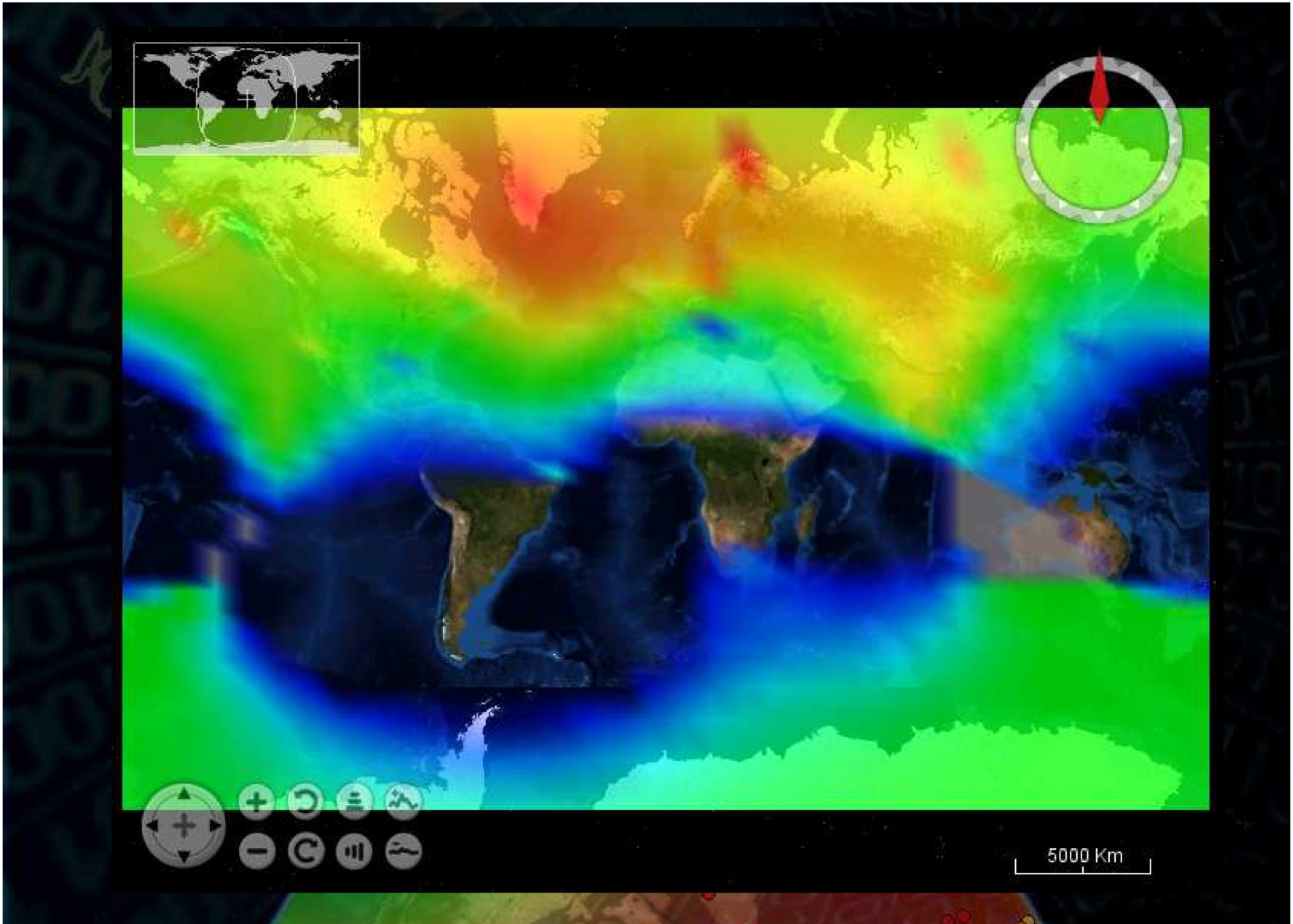
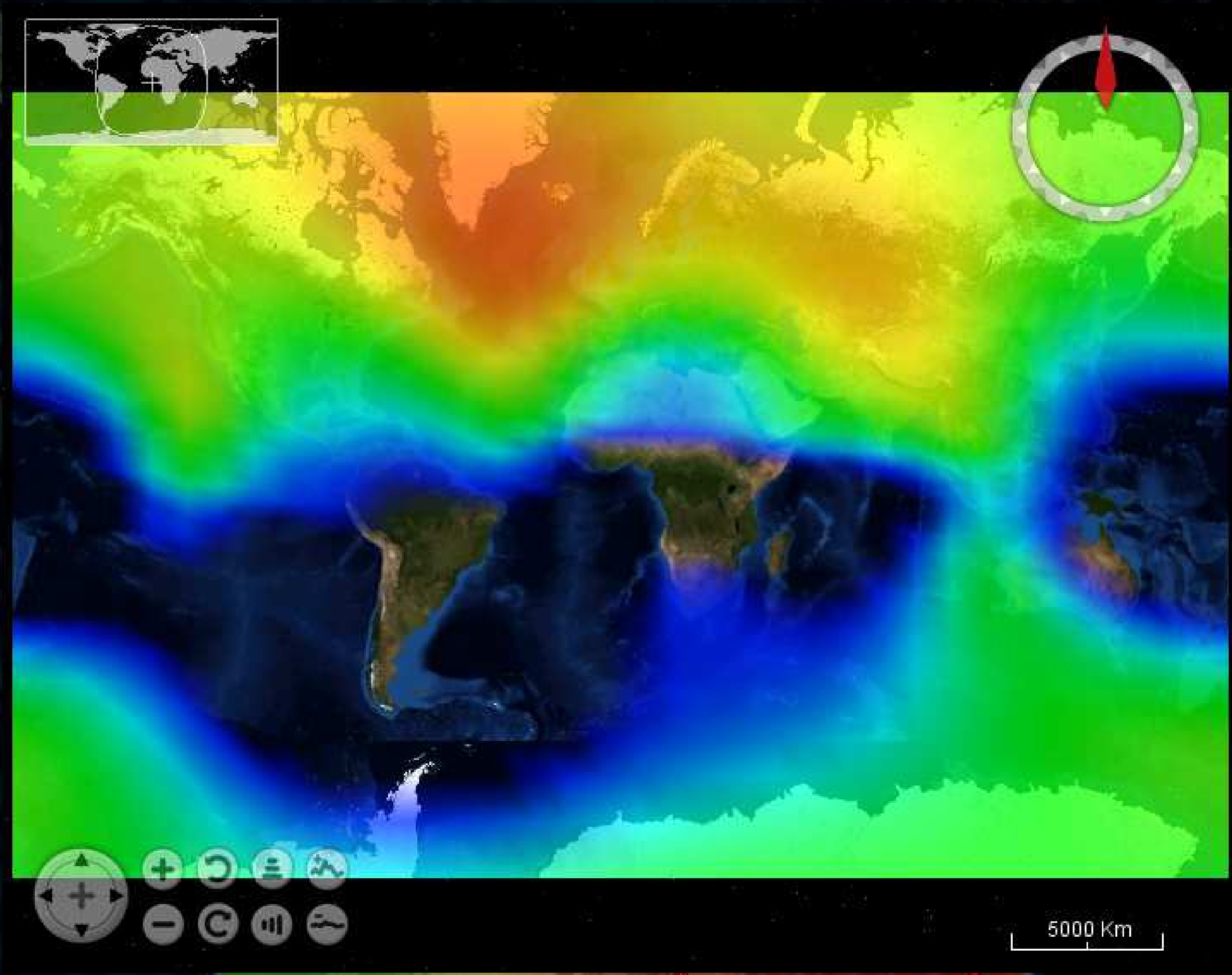

5000 Km


5000 Km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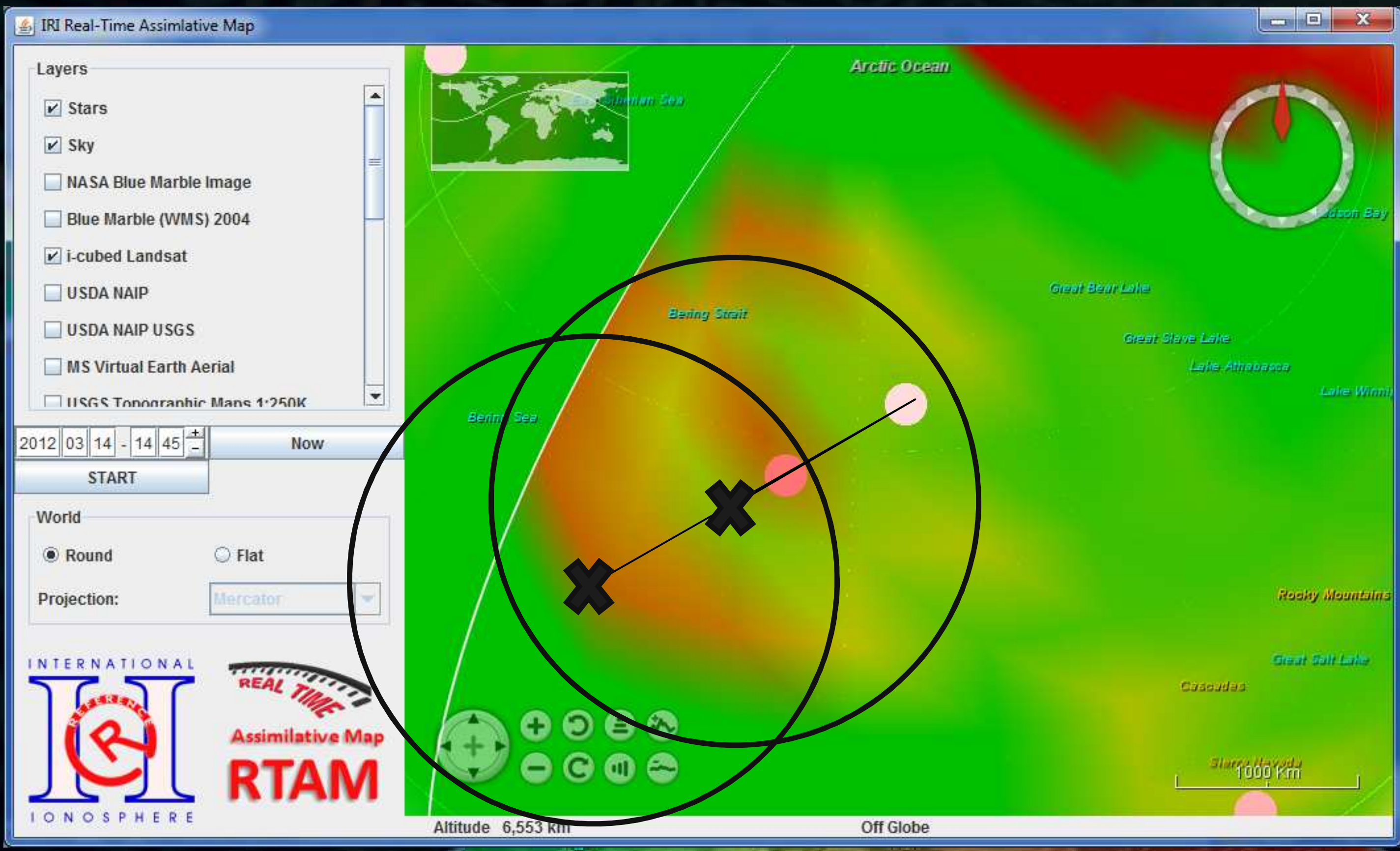
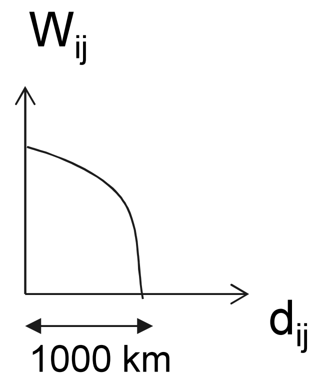
Synaptic Weight Engineering

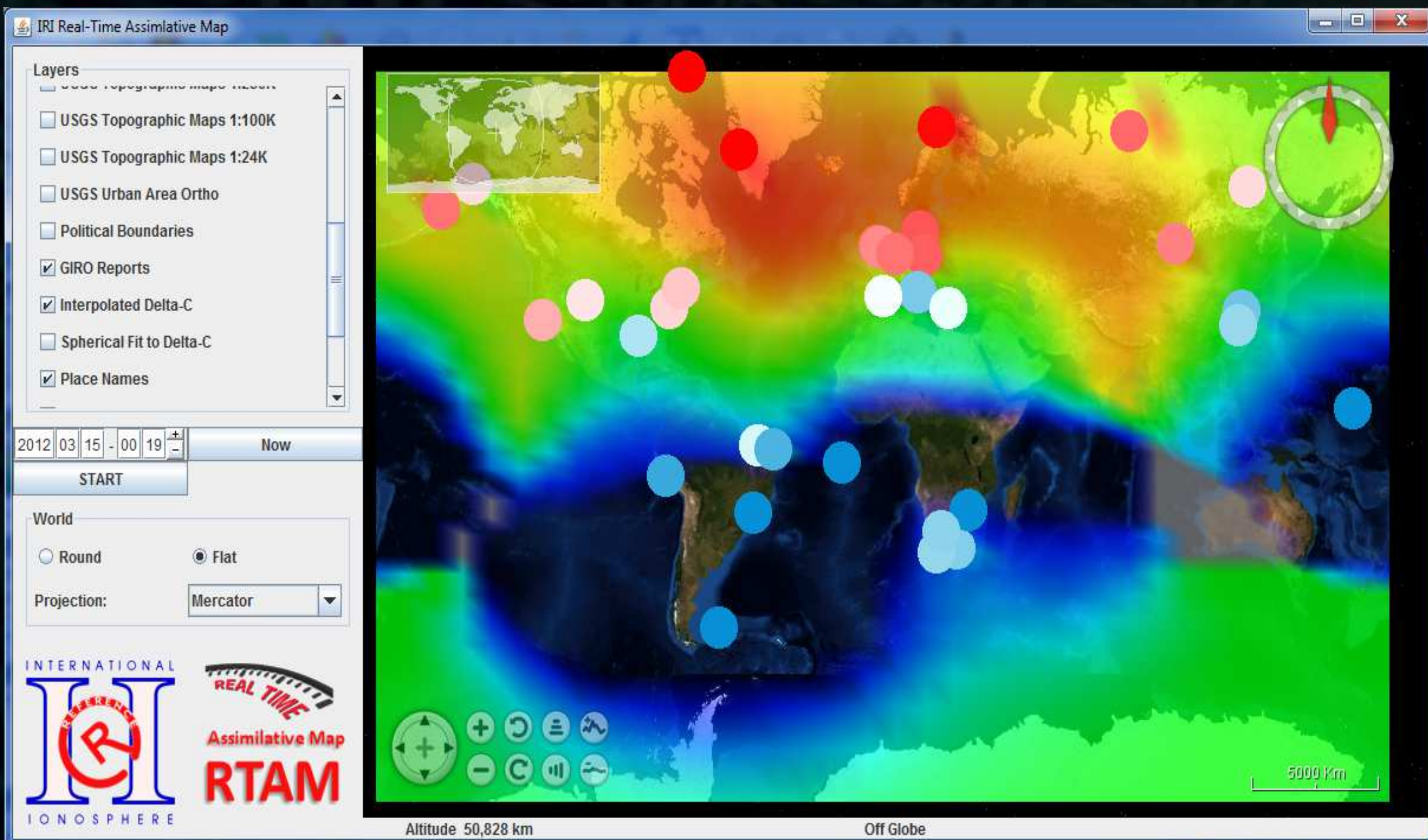


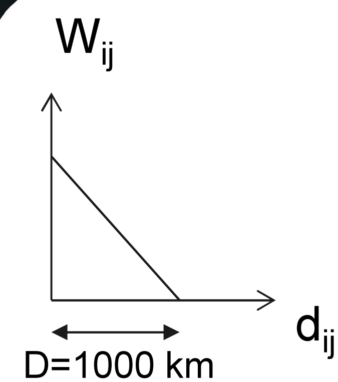


$$V_i = \frac{\sum_{j \neq i} W_{ij} V_j}{\sum_{j \neq i} W_{ij}}$$

$$W_{ij} = \sin\left(\pi \frac{d_{ij}}{2D} \right)$$

Synaptic Weight Engineering (2)

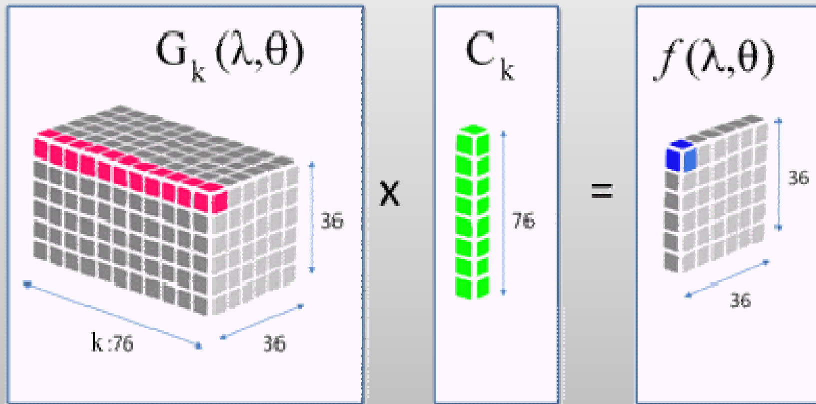




$$V_i = \frac{\sum_{j \neq i} W_{ij} V_j}{\sum_{j \neq i} W_{ij}}$$

$$W_{ij} = 1 - \frac{d_{ij}}{D}$$

Expansion to Jones-Garret 76 coefficients

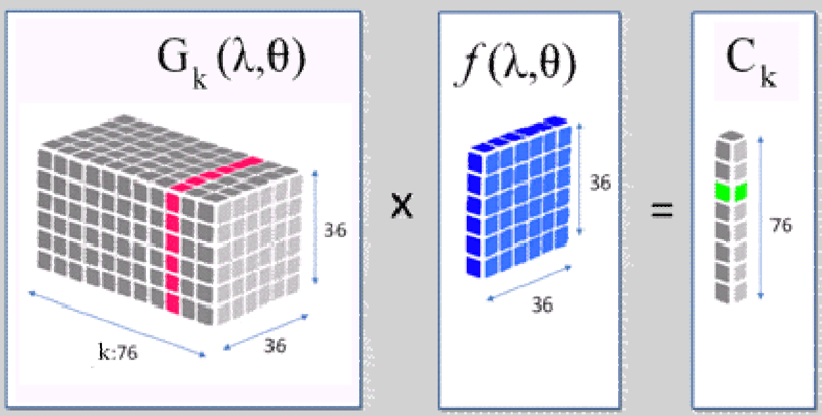


Synthesis from coefficients

$$f(\lambda_q,\theta_r) = \sum_{k=0}^{75} C_k G_k(\lambda_q,\theta_r)$$

$$q = 1..36,\ r = 1..36$$

$$G_k(\lambda_q,\theta_r) = \sin^n(\chi_{qr})\cos^m(\lambda_q)\begin{bmatrix}\cos(m\theta_r)\\ \sin(m\theta_r)\end{bmatrix}$$



Expansion into coefficients

Gk are not orthogonal

Orthnormalization of Gk is needed

Classic
Longitudinal
Harmonics
8^{th} order

$$G_k = \overbrace{\left(\sin^n \chi\right)}^{\text{B-field factor}} \cdot \overbrace{\left(\cos^m \lambda\right)}^{\text{Pole suppressor}} \cdot \begin{bmatrix} \cos m\theta \\ \sin m\theta \end{bmatrix}$$

modip

e.g., $G_0 = 1$, $G_2 = \sin^2\chi$ not mutually orthogonal

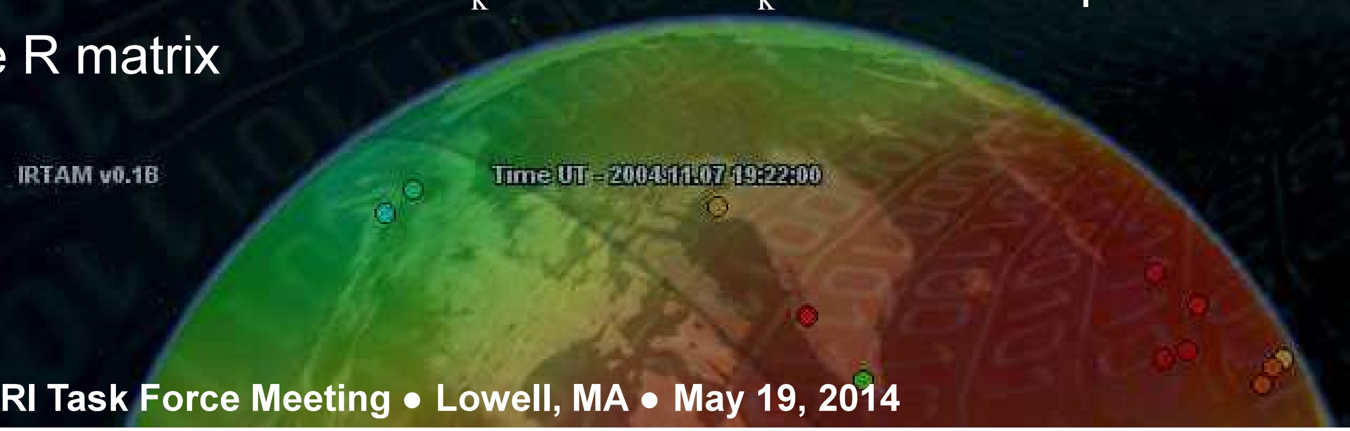
Use Fk instead of Gk for the fitting

Following suggestions from Jones and Gallet, 1962:

→(1) Use orthonormalization to obtain F_k from G_k
- Jones/Gallet used Gram-Schmidt process
  - Numerical accuracy problems
  - Had to apply G.S. algorithm twice
- We use QR decomposition

→(2) Use a fitting algorithm to obtain c_k for F_k

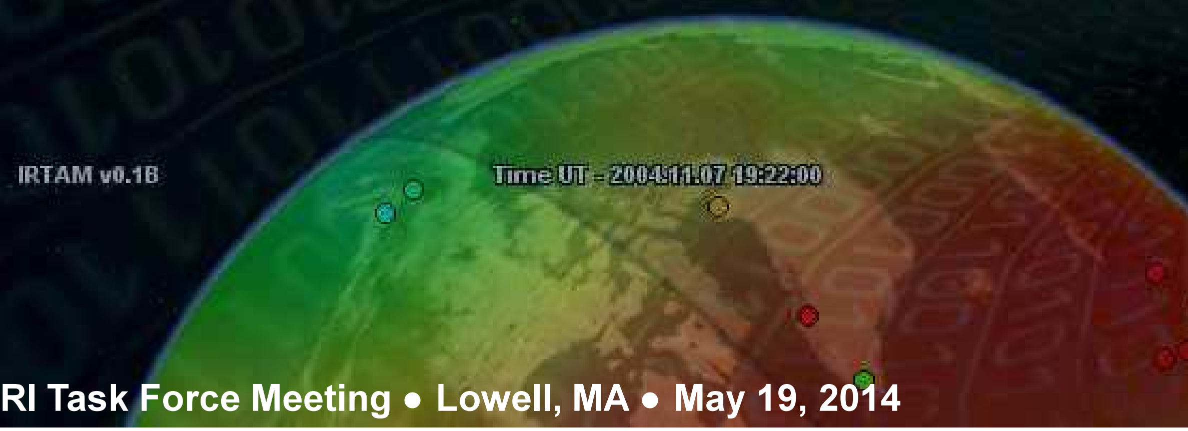
→(3) "Unwind" coefficients c_k to obtain C_k that are compatible with G_k
- Use R matrix



76-order Least Square Fit, no kidding

- Finding c_k coefficients to fit F_k functions to data f
  - Multiple approaches tried
  - This is 76-order over-determined fitting task
  - Inversion of [76 x 1296] matrices is not reliable
  - Current best performer: Approximate LS solution

$$
\begin{aligned}
c_0 &= \mathbf{f} \cdot \mathbf{F_0} \\
\mathbf{r_1} &= \mathbf{f} - c_0 \mathbf{F_0} \\
c_1 &= \mathbf{r_1} \cdot \mathbf{F_1} \\
\mathbf{r_2} &= \mathbf{r_1} - c_1 \mathbf{F_1} \\
c_n &= \mathbf{r_n} \cdot \mathbf{F_n} \\
\mathbf{r_{n+1}} &= \mathbf{r_n} - c_n \mathbf{F_n}
\end{aligned}
$$



Gambit

GAMBIT ENVIRONMENT:
SOFTWARE DEMO

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