

IRI in Python for Rapid Global Runs Global-IRI

Victoriya V. Forsythe Sarah McDonald, Kenneth Dymond, Douglas P. Drob, Bruce Fritz, Angeline G. Burrell

Naval Research Laboratory, DC, USA

Distribution statement A. Approved for public release. Distribution is unlimited. This work was supported by the Office of Naval Research



Motivation: ANCHOR

•

۲

- A new DA model is being developed at NRL.
- It extracts anchor (hence the name) points from data and assimilates them in 2D maps using Kalman Filter.





- In order to try different assimilative techniques, including Ensemble Kalman Filter, we needed an ionospheric model that would produce rapid global outputs of the main parameters.
- Unfortunately, there is no such option to run IRI-2020 globally
- Usually the irregular grid is used for the DA, requiring point-by-point model run



L Introduction: NmF2, hmF2

- The F2-peak is the most important parameter for any ionospheric model, because it is the highest value reached in the ionosphere [Bilitza et al., 2022]
- IRI uses CCIR coefficients (or URSI coefficients (same format)) to obtain the NmF2 and hmF2.

JOURNAL OF RESEARCH of the National Bureau of Standards—D. Radio Propagation Vol. 66D, No. 4, July–August 1962

Representation of Diurnal and Geographic Variations of Ionospheric Data by Numerical Methods*

William B. Jones and Roger M. Gallet





No. 337

ADVANCES IN IONOSPHERIC MAPPING BY NUMERICAL METHODS



- Jones & Gallet, 1962 applied Least Squares method to find coefficients for global and diurnal functions that best describe the variations in the mean values of the ionospheric parameters.
- The diurnal variation of the parameters is represented by Fourier analysis of the 24-hour data from each station.
- Then the worldwide geographic variation of each Fourier coefficients is expanded in a series of functions similar to surface spherical harmonics.
- The noise is reduced by the truncations of the series.
- Result: table of coefficients that describe diurnal and geographical variation of the monthly mean ionospheric parameters.





CCIR files

- Inside one can find 4 columns of coefficients
- Very inconvenient to read (no space delimiters) and hard to understand what is what
- Inside coefficients for 2 levels of solar activity for foF2 and M3000
- Both have different sizes due to the truncation of series
- 2858 coefficients

• • •	ccir11.asc — Edited		
0 5			ccir11.asc
0.5	2390593E+01-0.50523029E-01-0.18/0401/E-01 0.12128915E-01		
0.7	9412190E-02-0.10031431E-01 0.21307201E-01-0.08002000E-02		aair10 aaa
0.3	0,022,0422-02 0.0000000000000000000000000000000000		cciriz.asc
_0.2	29390149L-01 0.93323400L+00-0.20397303L-01 0.10940776L+00 20760527E+00_0 37003383E+00_0 23273268E+00 0 80/80601E_01		
0.3	33996305E_01 0 32839003E+00_0.23273200E+00 0.03400031E+00	6	aair12 aaa
_0 2	7873784E-01 0 11766478E-01 0 80531130E+01 0 13981774E+01		cciri3.asc
0.4	17361958E+00-0.11388183E+00 0.77816737E+00-0.17388150E+00		
0.2	29099104F+00 0.29059123E-01-0.37210885F+00-0.11191850F+00		agir14 aga
-0.4	13733008E-01 0.12193082E+00-0.32639468E+00-0.13390853E+02		CCIT 14.aSC
0.6	2356526E+00 0.24597554E+01 0.44970918E+01 0.85659552E+01		
0.4	10355296E+01-0.79231381E+00-0.67203265E+00-0.47442737E+01	4	agir15 aga
0.2	21074810E+01 0.33913586E+01-0.10161761E+00-0.69574153E+00		CCILID.aSC
-0.3	32273560E+02-0.56248417E+01-0.58702965E+01-0.43174982E+01		
-0.3	32914643E+01 0.14731911E+01-0.84157687E+00-0.18629679E+00		agir16 ago
0.3	36630037E+01-0.49589828E+00 0.42669845E+00-0.39217409E+00		ccir io.asc
0.1	L5235479E+01-0.10364820E+00-0.17449905E+02-0.18375044E+02		
-0.1	L6429411E+02-0.42843178E+02-0.18512333E+02 0.29954524E+01	6	agir17 ago
0.4	4427662E+01 0.22331482E+02-0.11312363E+02-0.17385393E+02		CCITI7.asc
0.1	L3743354E+01 0.49287653E+01 0.35317551E+02 0.78040113E+01		
0.2	22017223E+02 0.19007372E+02 0.51486945E+01-0.32355106E+01	6	ooir10 200
-0.7	70289177E+00-0.18949838E-01-0.10833933E+02 0.30533838E+01		CCII IO.aSC
-0.1	L5614654E+01 0.34174812E+00-0.33425496E+01 0.10955015E+03		
0.6	54495300E+02 0.39307384E+02 0.21447481E+02 0.88321732E+02	6	coir10 aco
0.3	36022030E+02-0.492/9366E+01-0.1126634/E+02-0.45660416E+02		CCILI9.asc
0.2	24308/01E+02 0.30402855E+02-0.3/914002E+01-0.12354/81E+02		
-0.1	L2009038E+02-0.34928/31E+01-0.30891//3E+02-0.2029/300E+02	-	coir20 asc
-0.2	203/03/4LT01 0.2390/24/LT01 0.2/101193LT01 0.10009334E+01		CCII 20.asc
0.1	34469433E+01-0 18371085E+03-0 78854736E+02-0 32724571E+02	-	
-0.8	36944246F+01-0.80539780F+02-0.31638607F+02 0.32864110F+01	5	ccir21 asc
0.1	2187758F+02 0.42042595F+02-0.23398046F+02-0.33907742F+02		001121.030
0.4	12148323E+01 0.12834593E+02 0.22537875E+01 0.19722799E+01	1.000	
0.1	L4214872E+02 0.11752549E+02 0.97573824E-01-0.41853258E+00	-	ccir22 asc
-0.1	L4487737E+01-0.91950291E+00-0.47050514E+01 0.19138944E+01		001122.030
ΛΟ	57494075,00 0 200000725,00 0 122020695,01 0 96102065,02		



2858 numbers represent 2 arrays:

$1976 \rightarrow [13, 76, 2]$

• the first array that contains coefficients for foF2

• • • Edited	1112	
ccir11.asc -	-	ccir11 asc
0.52396593E+01-0.56523629E-01-0.18704617E-01 0.12128915E-01	_	001111.000
0.79412190E-02-0.10031431E-01 0.21567261E-01-0.68602660E-02	1111	
0.37022342E-02 0.78359339E-02 0.63161603E-02-0.10695397E-01		ccir12.asc
0.29390149E-01 0.93325400E+00-0.2899/503E-01 0.10946//8E+00		
-0.30/0952/E+00-0.3/993383E+00-0.232/3208E+00 0.89480091E-01	L	
0.33090303E-01 0.32039003E+00-0.01993349E-01-0.14340941E+00 _0 27823284E_01 0 11266428E_01 0 80531130E±01 0 13081724E±01		ccir 13.asc
0.47361958E+00-0.11388183E+00 0.77816737E+00-0.17388150E+00		
0.29099104E+00 0.29059123E-01-0.37210885E+00-0.11191850E+00	6	agir14 ago
-0.43733008E-01 0.12193082E+00-0.32639468E+00-0.13390853E+02		CCII 14.aSC
0.62356526E+00 0.24597554E+01 0.44970918E+01 0.85659552E+01	-	
0.40355296E+01-0.79231381E+00-0.67203265E+00-0.47442737E+01	6	ccir15 asc
0.21074810E+01 0.33913586E+01-0.10161761E+00-0.69574153E+00		CCI110.43C
-0.32273560E+02-0.56248417E+01-0.58702965E+01-0.43174982E+01	1000	
-0.32914643E+01 0.14/31911E+01-0.8415/68/E+00-0.186296/9E+00		ccir16 asc
0.3003003/E+01-0.49389828E+00 0.42009845E+00-0.3921/409E+00 0.15235470E+01-0.10364920E+00-0.17440005E+02-0.19275044E+02		001110.000
-0.16720711E+02-0.72873178E+02-0.18512333E+02-0.200575044E+02		
0.44427662F+01 0.22331482F+02-0.11312363F+02-0.17385393F+02		ccir1/.asc
0.13743354E+01 0.49287653E+01 0.35317551E+02 0.78040113E+01	_	
0.22017223E+02 0.19007372E+02 0.51486945E+01-0.32355106E+01	L	
-0.70289177E+00-0.18949838E-01-0.10833933E+02 0.30533838E+01		ccir i8.asc
-0.15614654E+01 0.34174812E+00-0.33425496E+01 0.10955015E+03		
0.64495300E+02 0.39307384E+02 0.21447481E+02 0.88321732E+02	6	coir10 aco
0.36022030E+02-0.49279366E+01-0.11266347E+02-0.45660416E+02		CCIT 19.asC
0.24308/01E+02 0.30402855E+02-0.3/914002E+01-0.12354/81E+02 0.150606595.02 0.540297515.01 0.209017725.02 0.262075065.02		
-0.13009030L+02-0.34920731L+01-0.30091773L+02-0.20297300L+02 -0.28576374E+01.0.23907247E+01.0.27161193E+01.0.10669554E+01.0.1066954E+01.0.000000000000000000000000000000000	-	ccir20 asc
0.12239296F+02-0.43662004F+01 0.20293267F+01 0.21851628F+00		CCI120.03C
0.34469433E+01-0.18371085E+03-0.78854736E+02-0.32724571E+02	100	
-0.86944246E+01-0.80539780E+02-0.31638607E+02 0.32864110E+01	-	ccir21.asc
0.12187758E+02 0.42042595E+02-0.23398046E+02-0.33907742E+02		
0.42148323E+01 0.12834593E+02 0.22537875E+01 0.19722799E+01	1.15	: 00
0.14214872E+02 0.11752549E+02 0.97573824E-01-0.41853258E+00		ccir22.asc
-0.1448//3/E+01-0.91950291E+00-0.4/050514E+01 0.19138944E+01		





- foF2 uses:
- 13 functions to describe diurnal variation
- 76 functions to describe global variation



U = [13], 76, 2] $D_k(t) = \mathbf{C}_{0,k} + \sum_{j=1}^{n} \left[\mathbf{C}_{2j-1,k} \sin(jT_0) + \mathbf{C}_{2j,k} \cos(jT_0) \right]$







$$U = [13, 76, 2]$$

 $\sin^Q(x) \cos^L(\lambda) \frac{\cos(L\theta)}{\sin(L\theta)}$

8-degree harmonic expansion, L=0-8

Truncations:

Q = [12, 12, 9, 5, 2, 1, 1, 1, 1]



- Grid is defined as 1D array of Lat and 1D array of Lon
- Suitable for irregular grid
- $1^{\circ} \times 1^{\circ}$ resolution gives $N_G = 65341$

k	$G_{k}(\lambda,\theta)$	k	$G_k(\lambda, \theta)$
0 1 2 3 4 5 6 7 8 9 10 11	l sín x sin ² x sin ³ x sin ⁴ x sin ⁵ x sin ⁵ x sin ⁶ x sin ⁷ x sin ⁸ x sin ⁹ x sin ¹⁰ x sin ¹¹ x	40 41 42 43 44 45 46 47 48 49 50 51	$\begin{array}{c} \sin^2 x \cos^2 \lambda \cos^2 \lambda \cos 2\theta \\ \sin^2 x \cos^2 \lambda \sin 2\theta \\ \sin^3 x \cos^2 \lambda \cos 2\theta \\ \sin^3 x \cos^2 \lambda \cos 2\theta \\ \sin^3 x \cos^2 \lambda \sin 2\theta \\ \sin^4 x \cos^2 \lambda \cos^2 \lambda \sin 2\theta \\ \sin^4 x \cos^2 \lambda \sin 2\theta \\ \sin^5 x \cos^2 \lambda \sin 2\theta \\ \sin^5 x \cos^2 \lambda \sin 2\theta \\ \sin^6 x \cos^2 \lambda \sin 2\theta \\ \sin^6 x \cos^2 \lambda \sin 2\theta \\ \sin^7 x \cos^2 \lambda \cos 2\theta \\ \sin^7 x \cos^2 \lambda \sin 2\theta \\ \sin^7 x \cos^2 \lambda \sin 2\theta \\ \sin^8 x \cos^2 \theta \\ \cos^2 \theta \\ \sin^8 x \cos^2 \theta \\ \sin^2 \theta \\ \cos^2 $
12 13	cos χ cos θ cos χ sin θ	53	$\sin^8 x \cos^2 \lambda \sin 2\theta$
14 15 16 17 18 19 20 21 22 23	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 $\sin^3 x \cos \lambda \sin \theta$ 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 $\sin^5 x \cos \lambda \sin \theta$ 23 $\sin^5 x \cos \lambda \sin \theta$ 24 $\sin^6 x \cos \lambda \sin \theta$ 25 $\sin^6 x \cos \lambda \sin \theta$ 26 $\sin^7 x \cos \lambda \sin \theta$ 28 $\sin^8 x \cos \lambda \cos \theta$ 29 $\sin^8 x \cos \lambda \sin \theta$ 30 $\sin^9 x \cos \lambda \sin \theta$ 31 $\sin^9 x \cos \lambda \sin \theta$ 32 $\sin^{10} x \cos \lambda \sin \theta$ 34 $\sin^{11} x \cos \lambda \sin \theta$	54 55 56 57 58 59 60 61 62 63	$\begin{array}{cccccccccccccccccccccccccccccccccccc$
24 25 26 27 28		64 65 66 67	$\begin{array}{cccc} \cos 4 & \lambda & \cos & \lambda \theta \\ \cos 4 & \lambda & \sin & \lambda \theta \\ \sin x & \cos 4 & \lambda & \cos & \lambda \theta \\ \sin x & \cos 4 & \lambda & \sin & \lambda \theta \end{array}$
29 30 31		68 69	cos ⁵ λ cos 5θ cos ⁵ λ sin 5θ
32 33 34 35		70 71	cos ⁶ λ cos 6θ cos ⁶ λ sin 6θ
36	$\cos^2 \lambda \cos 2\theta$	72 73	cos ⁷ λ cos 7θ cos ⁷ λ sin 7θ
$\begin{array}{c c} 31 & \cos^2 \lambda \sin 2\theta \\ 38 & \sin x \cos^2 \lambda \cos 2\theta \\ 39 & \sin x \cos^2 \lambda \sin 2\theta \end{array}$	7 4 75	cos ^θ λ cos 8θ cos ⁸ λ sin 8θ	

	k $G_k(\lambda, \theta)$	k	$G_{k}(\lambda, \theta)$
U.S. NAVAL CABORATORY Global Functions F _G	$ \begin{array}{c cccc} 0 & 1 \\ 1 & \sin x \\ 2 & \sin^2 x \\ 3 & \sin^3 x \\ b & \sin^4 x \end{array} $	40 41 42 43 44	$\begin{array}{c} \sin^2 x \cos^2 \lambda \cos 2\theta \\ \sin^2 x \cos^2 \lambda \sin 2\theta \\ \sin^3 x \cos^2 \lambda \cos 2\theta \\ \sin^3 x \cos^2 \lambda \sin 2\theta \\ \sin^4 x \cos^2 \lambda \cos 2\theta \end{array}$
<i>U</i> = [13, 76, 2] <i>G</i> , k=1 <i>G</i> , k=	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	45 46 47 48 49 50 51 52 52 53	$\sin^{4} x \cos^{2} \lambda \sin 2\theta$ $\sin^{5} x \cos^{2} \lambda \cos 2\theta$ $\sin^{5} x \cos^{2} \lambda \sin 2\theta$ $\sin^{6} x \cos^{2} \lambda \cos 2\theta$ $\sin^{6} x \cos^{2} \lambda \sin 2\theta$ $\sin^{7} x \cos^{2} \lambda \cos 2\theta$ $\sin^{7} x \cos^{2} \lambda \sin 2\theta$ $\sin^{8} x \cos^{2} \lambda \cos 2\theta$ $\sin^{8} x \cos^{2} \lambda \sin 2\theta$
G, k=22 60 60 60 40 60 60 60 60 90 100 150 100 10	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 $\sin^5 x \cos \lambda \cos \theta$ 23 $\sin^5 x \cos \lambda \sin \theta$	54 55 56 57 58 59 60 61 62 63	$\begin{array}{cccccccccccccccccccccccccccccccccccc$
$\begin{array}{c} -40 \\ -60 \\ -80 \\ -150 \\ -150 \\ -150 \\ -150 \\ -150 \\ -150 \\ -150 \\ -150 \\ -100 \\ -50 \\ -50 \\ -50 \\ -50 \\ -50 \\ -50 \\ -50 \\ -50 \\ -50 \\ -0.24 \\ -0.24 \\ -0.24 \\ \hline \end{array}$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	64 65 66 67 68 69	$\begin{array}{cccc} \cos 4 & \lambda & \cos & 4\theta \\ \cos 4 & \lambda & \sin & 4\theta \\ \sin x & \cos 4 & \lambda & \cos & 4\theta \\ \sin x & \cos 4 & \lambda & \sin & 4\theta \\ \end{array}$ $\begin{array}{cccc} \cos 5 & \lambda & \cos & 5\theta \\ \cos 5 & \lambda & \sin & 5\theta \end{array}$
$\sin^{Q}(x) \cos^{L}(\lambda) \frac{\cos(L\theta)}{\sin(L\theta)} = 0.00$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	70 71 72 73 74 75	$\frac{\cos^{6} \lambda \cos 6\theta}{\cos^{6} \lambda \sin 6\theta}$ $\frac{\cos^{7} \lambda \cos 7\theta}{\cos^{7} \lambda \sin 7\theta}$ $\frac{\cos^{8} \lambda \cos 8\theta}{\cos^{8} \lambda \sin 8\theta}$



U.S. NAVAL LABORATORY HOW Global-IRI does it



- Evaluation involves matrix multiplication instead of additions in the closed loops
- Suitable for high spatial and temporal resolution grids
- The output is 24-hour global distribution



$$D_{k}(t) = \mathbf{C}_{0,k} + \sum_{j=1}^{H} \left[\mathbf{C}_{2j,k} \cos(jT_{0}) + \mathbf{C}_{2j-1,k} \sin(jT_{0}) \right]$$

index	j	function
0	0	1
1	1	$sin(T_0)$
2	1	$\cos(T_0)$
3	2	$sin(2T_0)$
4	2	$\cos(2T_0)$
5	3	$sin(3T_0)$
6	3	$\cos(3T_0)$
	•••	
13	6	$\cos(6T_0)$

U = [13, 76]

Calculate F_D for the array of UT with size $[N_T]$ $F_D = [N_T, 13]$



Global Functions to Matrix Form

k	$G_k(\lambda, \theta)$	k	$G_{k}(\lambda, \theta)$	
0 1 2 3 4 5 6 7 8 9 10 11	l sin x sin ² x sin ³ x sin ⁴ x sin ⁵ x sin ⁶ x sin ⁷ x sin ⁸ x sin ⁹ x sin ¹⁰ x sin ¹¹ x	40 41 43 45 46 47 48 49 50 51 52	$\begin{array}{c} \sin^2 x \cos^2 \lambda \cos^2 \theta \\ \sin^2 x \cos^2 \lambda \sin^2 \theta \\ \sin^3 x \cos^2 \lambda \cos^2 \theta \\ \sin^3 x \cos^2 \lambda \cos^2 \theta \\ \sin^3 x \cos^2 \lambda \sin^2 \theta \\ \sin^4 x \cos^2 \lambda \sin^2 \theta \\ \sin^4 x \cos^2 \lambda \sin^2 \theta \\ \sin^5 x \cos^2 \lambda \sin^2 \theta \\ \sin^6 x \cos^2 \lambda \sin^2 \theta \\ \sin^6 x \cos^2 \lambda \sin^2 \theta \\ \sin^7 x \cos^2 \lambda \sin^2 \theta \\ \sin^7 x \cos^2 \lambda \sin^2 \theta \\ \sin^6 x \cos^2 \lambda \cos^2 \theta \\ \sin^6 x \cos^2 \lambda \cos^2 \theta \\ \sin^6 x \cos^2 \lambda \cos^2 \theta \\ \end{array}$	
12 13 14 15 16 17	$\begin{array}{c} \cos \ \lambda \ \cos \ \theta \\ \cos \ \lambda \ \sin \ \theta \\ \sin \ x \ \cos \ \lambda \ \cos \ \theta \\ \sin \ x \ \cos \ \lambda \ \sin \ \theta \\ \sin^2 \ x \ \cos \ \lambda \ \sin \ \theta \\ \sin^2 \ x \ \cos \ \lambda \ \sin \ \theta \end{array}$	53 54 55 56 57	$\begin{array}{c c} \sin^8 x \cos^2 \lambda \sin 2\theta \\ & \cos^3 \lambda \cos 3\theta \\ & \cos^3 \lambda \sin 3\theta \\ \sin x \cos^3 \lambda \cos 3\theta \\ \sin x \cos^3 \lambda \sin 3\theta \end{array}$	
18 19 20 21 22 23 23	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 $\sin^5 x \cos \lambda \cos \theta$ 24 $\sin^6 x \cos \lambda \cos \theta$ 25 $\sin^6 x \cos \lambda \sin \theta$ 26 $\sin^7 x \cos \lambda \cos \theta$ 27 $\sin^7 x \cos \lambda \sin \theta$ 28 $\sin^8 x \cos \lambda \cos \theta$		58 59 60 61 62 63	$\begin{array}{c} \sin^2 \ x \ \cos^3 \ \lambda \ \cos^3 \theta \\ \sin^2 \ x \ \cos^3 \ \lambda \ \sin^3 \theta \\ \sin^3 \ x \ \cos^3 \ \lambda \ \cos^3 \theta \\ \sin^3 \ x \ \cos^3 \ \lambda \ \sin^3 \theta \\ \sin^4 \ x \ \cos^3 \ \lambda \ \cos^3 \theta \\ \sin^4 \ x \ \cos^3 \ \lambda \ \sin^3 \theta \end{array}$
25 26 27 28		64 65 66 67	$\begin{array}{c} \cos^4 \ \lambda \ \cos \ 4\theta \\ \cos^4 \ \lambda \ \sin \ 4\theta \\ \sin \ x \ \cos^4 \ \lambda \ \cos \ 4\theta \\ \sin \ x \ \cos^4 \ \lambda \ \cos \ 4\theta \\ \sin \ x \ \cos^4 \ \lambda \ \sin \ 4\theta \end{array}$	
30 31 32	$ \frac{\sin^{9} x \cos \lambda \cos \theta}{\sin^{9} x \cos \lambda \sin \theta} $	68 69	cos ⁵ λ cos 5θ cos ⁵ λ sin 5θ	
33 34 35	$ \begin{array}{c} \sin^{10} x \cos \lambda \sin \theta \\ \sin^{10} x \cos \lambda \cos \theta \\ \sin^{10} x \cos \lambda \sin \theta \end{array} $	70 71	cos ^e λ cos 6θ cos ^e λ sin 6θ	
36	$\frac{\cos^2 \lambda \cos 2\theta}{\cos^2 \lambda \sin 2\theta}$	72 73	cos ⁷ λ cos 7θ cos ⁷ λ sin 7θ	
$\begin{array}{c} \cos \lambda \sin 2\theta \\ 38 \\ \sin x \\ \cos^2 \lambda \\ \cos^2 \lambda \\ \sin 2\theta \end{array}$	74 75	cos ^e λ cos 8θ cos ^e λ sin 8θ		

U = [13, 76]

Calculate F_G for the array of grid with size $[N_G]$ $F_G = [76, N_G]$



U = [13, 76] $F_G = [76, N_G]$ $F_D = [N_T, 13]$

$$GAMMA = (F_D U) F_G = [N_T, N_G]$$

- To obtain the same result, it would require to execute IRI for $N_T * N_G$ times
- 6,272,736 times
- Same can be done in 3 seconds

• Suitable for high spatial and temporal resolution grids





- This work will soon be published and the code will be made available to the community as a Python package.
- Stay tuned for the first release.