IRI

International Reference Ionosphere
Introduction, Current Status, and Future Plans

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What is IRI ?

- IRI is the international standard for the most important plasma parameters in the Earth ionosphere.
- IRI is the result of several decades of international collaborations in the framework of a project jointly sponsored by the ***Committee on Space Research (COSPAR)*** and the ***International Union of Radioscience (URSI).***
- COSPAR's prime interest is in a general description of the ionosphere as part of the terrestrial environment for the evaluation of environmental effects on spacecraft and experiments in space.
- URSI's prime interest is in a reference model for defining the background ionosphere for radiowave propagation studies and applications.
- By charter the model should be primarily based on ***experimental evidence*** using all available ground and space data sources and **should not depend on the evolving theoretical understanding of ionospheric processes**.
- As new data become available and as older data sources are fully evaluated and exploited, the model should be *revised* in accordance with these new results.
- Where discrepancies exist between different data sources the IRI team has facilitate critical review and discussions to determine the ***reliability of the different data sets*** and to establish guidelines on which data should be used for IRI modeling.

Which Parameters in what Range

IRI describes monthly averages of

- electron density
- electron temperature
- ion temperature
- ion composition (O^+, H^+, He^+, N^+, NO^+, O_2^+, Cluster ions)

IRI represents variations with

- altitude (50km – 2000 km)
- latitude, longitude (geographic or geomagnetic)
- date and time of day

External drivers:

- solar indices: F10.7 (daily, 81-day, 365-day), R (13 month)
- ionospheric index: IG (13 month)
- magnetic indices: ap and kp (3-hour, daily)

Additional output parameters:

- vertical total electron content (vTEC)
- ion drift at magnetic equator
- occurrence probability for spread-F and for F1 layer

IRI Specifics

- Combining the global picture recorded by satellites for different local times and for different levels over solar activity with the 24/7 365 analysis provided by ground stations.
- Modular approach, e.g., global models for profile anchor points: T_e at different heights from ISIS, AE, IK connected by Epstein functions.
- Switches to choose different model options; e.g. *hmF2* models using different data sources, topside N_e profile models using different formalisms.
- New, better models are easily phased in with validation help from the users
- Avoiding introduction of interdependence between parameters because replacing one parameter model will affect the related parameter.
- IRI drivers: F10.7 (daily, 81-day, 356-day), R (13 month), IG (13 month), Ap, Kp (3-hour, daily)
- User input of measured parameters: *Nm*F2/*fo*F2, *hm*F2/M(3000)F2, *Nm*F1/*fo*F1, *Nm*E/*fo*E, *hm*E, B_0, B_1

Empirical Models	Theoretical Models
Based on ground and/or space data	Consider the production, loss, and transport of ionospheric electrons and ions, and obtain the electron density from the balance of these processes
Use appropriate mathematical functions to represent the characteristic variation patterns seen in long data records;	Use a numerical (iterative) scheme to solve Boltzmann equations.
Do not depend on our evolving understanding of the processes that shape the ionosphere environment	Theoretical models are primarily used in an investigative mode, to elucidate specific processes and their effects on the ionosphere
Empirical models are, in general, available to users in the form of a computer program, and can be readily adapted to a specific problem.	Theoretical models require considerable computer time, even on fast machines, and their complex computer code and logic make it difficult for people other than the model developers themselves to apply the model to a specific problem.

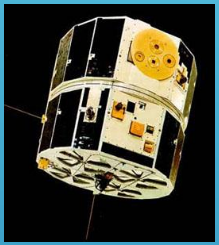
In actual fact, most ionospheric models are hybrids, using empirical as well as theoretical elements. An empirical model, for example, may use theoretical values to fill data gaps, whereas a theoretical model may use a data-based mapping for specific parameters as input (e.g., to represent neutral densities and temperature), or as a normalization tool for areas of model-data discrepancies.

Data Used to Develop IRI

- ❖ The worldwide network of **ionosondes** (150–170 stations) going back to the fifties, and in recent years aided by the steadily increasing network of **digisondes** (~60):
  >> *fo*F2, *M*(3000)F2 *hm*F2 and bottomside parameters B_0 and B_1.

- ❖ **Incoherent scatter radars** (ISRs) at Jicamarca, Arecibo, St. Santin, Millstone Hill:
  >> electron density & temperature, ion temp. & composition top- & bottom-side.

- ❖ **Topside sounder** measurements by the Alouette-1 and -2, ISIS-1 and -2, Intercosmos 19, and ISS-b satellites:
  >> electron density profile in the topside ionosphere.



- ❖ **Satellite in situ** measurements from the 60s to the present extending over more than five solar cycles:
  >> global morphology of electron and ion temperature and ion composition.

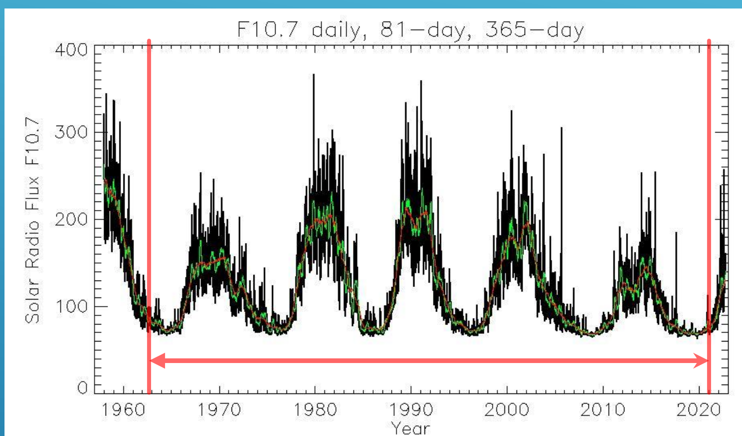
- ❖ Compilations of **rocket** data:
  >> electron density and ion composition in the D region and bottomside E region.

- ❖ **Global Navigation Satellite System** (GNSS) satellite data:
  >>GIM v*TEC* data for comparisons and real-time adjustments.

- ❖ **Radio occultation** (RO) data from COSMIC and other satellites:
  >> global modeling of *hm*F2 and for comparisons and real-time adjustments.

The IRI working group has been proactive in finding new data sources and in fully exploiting older data sources (like the Alouette/ISIS topside sounder data). Special IRI workshops discussed the most reliable data sources for the lower ionosphere and helped to resolve discrepancies that existed early on between measurements from the ground and in space.

In-situ Satellite Data Used for developing IRI



- Covering 5 solar cycles (58 years)
- Altitudes range from 200 km to 4,300 km
- Mostly high inclination orbits with a few low inclination satellites.

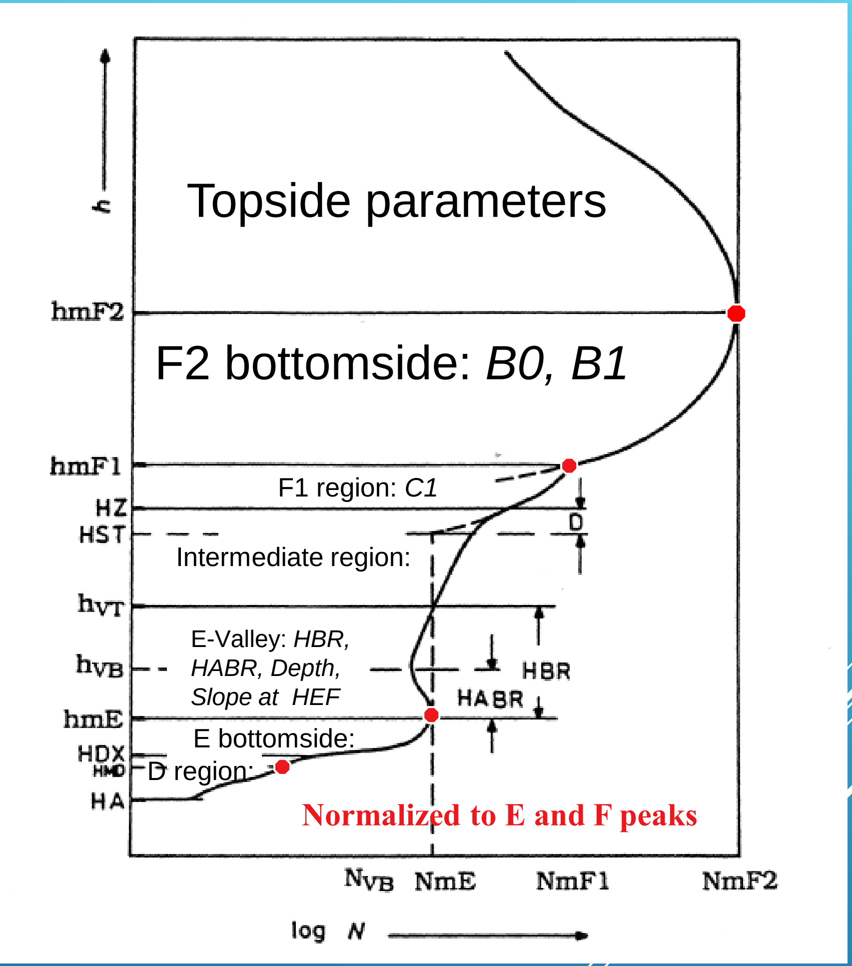
Satellite	Time period	Altitude (km)	Latitude (deg)	LT (hr)
Alouette-1	9/1962–12/1971	990–1,070	[−80, +80]	0–24
Explorer 31	11/1965–8/1968	500–3,010	[−79, +79]	0–24
Alouette-2	12/1965–7/1972	500–3,000	[−80, +80]	0–24
ISIS-1	2/1969–5/1980	580–3,550	[−88, +88]	0–24
OGO-6	12/1969–4/1971	390–1,090	[−82, +82]	0–24
ISIS-2	4/1971–8/1979	1,360–1,460	[−88, +88]	0–24
AEROS-A	1/1973–8/1973	200–870	[−83, +83]	3, 15 fixed
AE-C	12/1973–12/1978	130–4,300	[−68, +68]	0–24
AEROS-B	7/1974–9/1975	140–880	[−83, +83]	4, 16 fixed
AE-D	10/1975–1/1976	140–3,700	[−90, +90]	0–24
AE-E	12/1975–5/1981	140–1,580	[−20, +20]	0–24
ISS-b	8/1978–7/1981	970–1,240	[−69, +69]	0–24
Intercosmos 19	3/1979–1/1981	500–1,020	[−74, +74]	0–24
Hinotori	2/1981–6/1982	560–640	[−31, +31]	0–24
DE-2	8/1981–2/1983	200–1,020	[−90, +90]	0–24
San Marco 5	4/1988–12/1988	170–590	[−3, +3]	0–24
Intercosmos 24	10/1989–11/1991	500–2,530	[−83, +83]	0–24
DMSP F10	12/1990–6/1993	730–860	[−90, +90]	8–20 fixed
DMSP F11	12/1991–6/1993	850–870	[−90, +90]	5–17 fixed
Intercosmos 25	12/1991–6/1993	440–3,110	[−83, +83]	0–24
SROSS C2	1/1995–12/2000	380–620	[−40, +45]	0–24
DMSP F13	3/1995–12/2005	840–880	[−90, +90]	5.75, 17.75
DMSP F12	1/1996–6/2002	840–890	[−90, +90]	9.5, 21.5
DMSP F14	1/1997–12/2005	840–880	[−90, +90]	9.5, 21.5
ROCSAT-1	3/1999–6/2004	560–665	[−35, +35]	0–24
DMSP F15	12/1999–12/2017	830–880	[−90, +90]	9.5, 21.5
KOMPSAT	6/2000–8/2001	~685	[−90, +90]	22.8
CHAMP	8/2000–2/2010	310–460	[−87, +87]	0–24
TIMED	12/2001–12/2009	625	[−74, +74]	0–24
GRACE	4/2002–4/2015	390–540	[−89, +89]	0–24
COSMIC I	4/2006–4/2020	490–870	[−72, +72]	0–24
C/NOFS	8/2008–11/2015	260–860	[−13, +13]	0–24
Swarm A, C	12/2013–12/2019	430–530	[−90, +90]	0–24
Swarm B	12/2013–12/2019	490–550	[−90, +90]	0–24
ICON	10/2019–6/2020	575–610	[−27, +27]	0–24

Built-up of the IRI electron density model

Global Variations:
- Spherical harmonics using modified magnetic coordinates (modip, invdip)
- Interpolation between grid points (Epstein functions, others)

Time Variations:
- Harmonics of different order
- Smooth transitions between day and night values

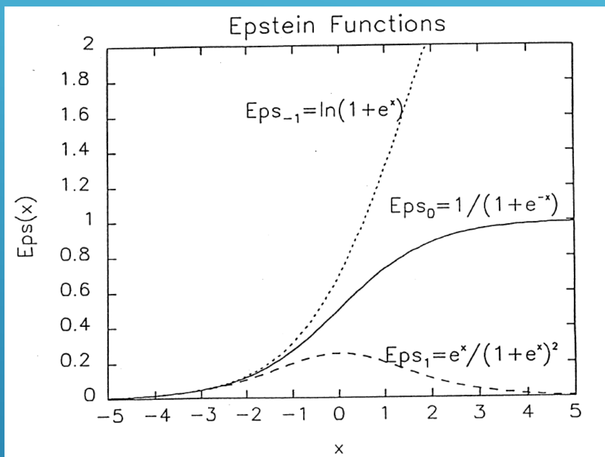
Height Variations:
- Epstein functions
- Polynomials

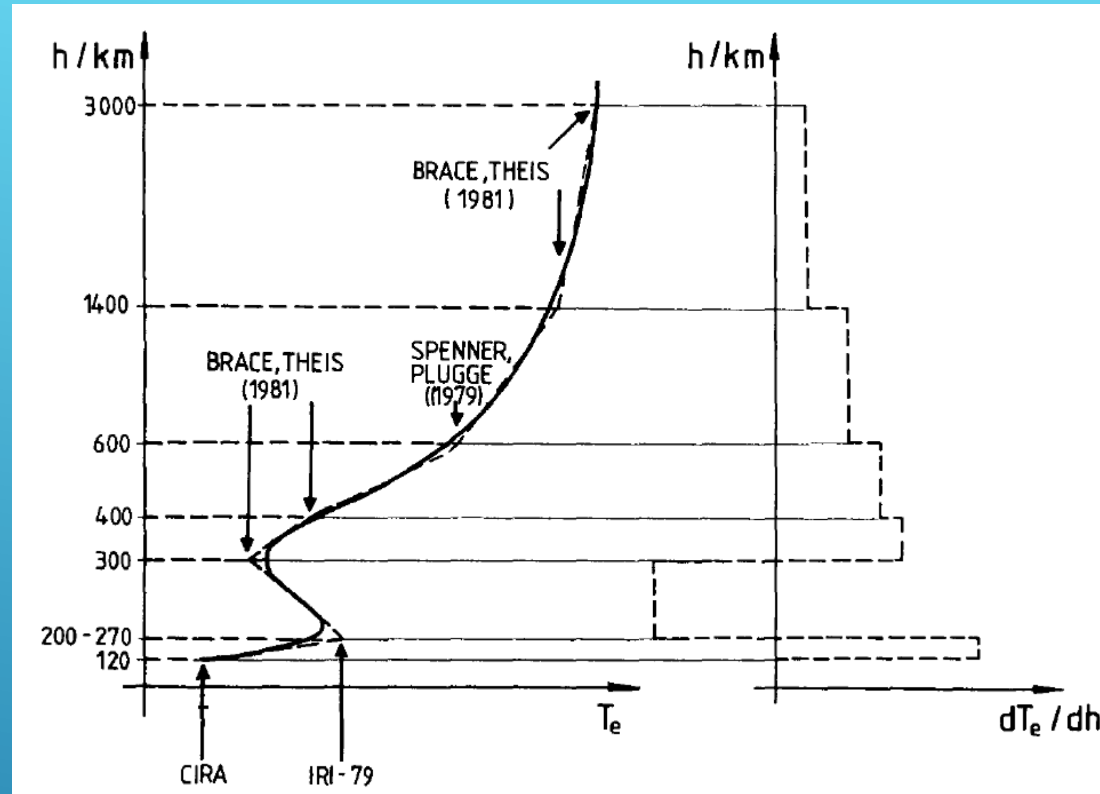


Global models for anchor points:

foF2/NmF2 foF1/NmF1, foE/NmE, foD/NmD, hmF2/M(3000)F2, hmF1 , hmE, hmD

Epstein functions





Eps_{-1} describes a transition, Eps_0 a step, and Eps_1 a layer.
By using $x=(h-h_i)/d_i$ each of these functions is centered at $h = h_i$ with the parameter d_i describing the width of the specific feature.

Eps_0 is used in IRI for:

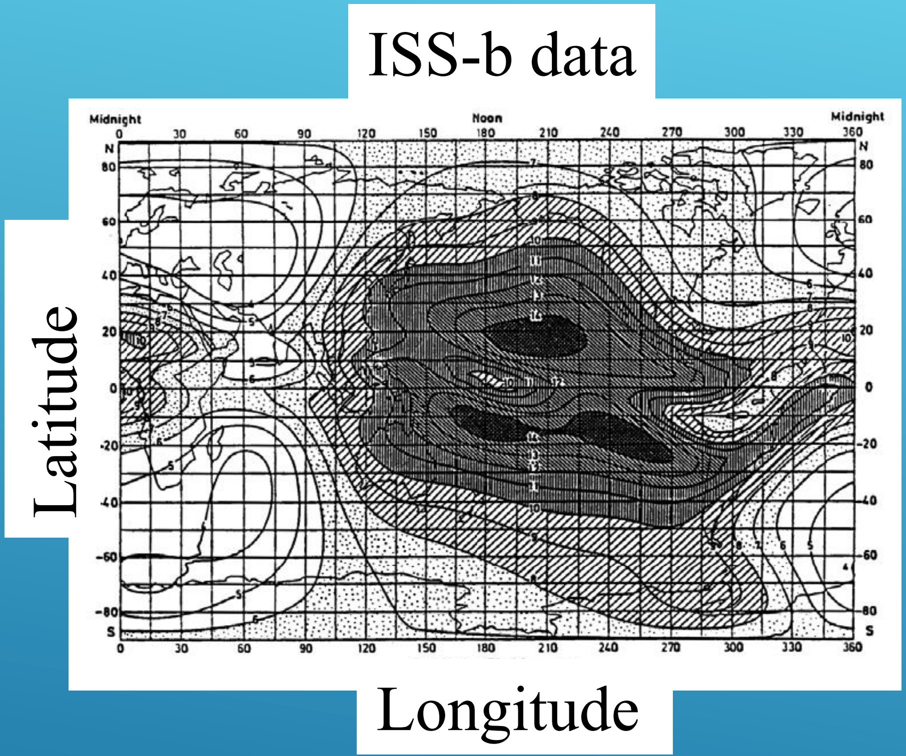
- Stepping from day to night values
- Connecting regions of constant gradient (Booker function)

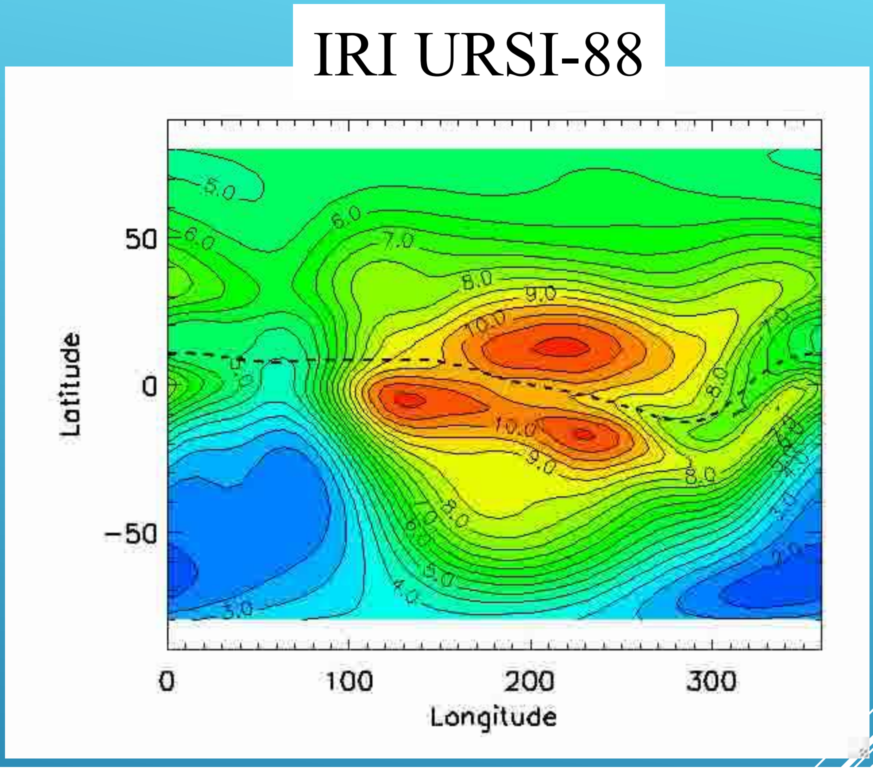
$$dT/dh = m_1+\Sigma_i\ (m_{i+1} - m_i)/(1+\exp[-(h-h_i)/d_i])$$

$$T = T(h_0) + m_1 \cdot (h - h_0) + \sum_{i=1}^{5} (m_{i+1} - m_1) \cdot d_1 \cdot \ln \frac{1 + \exp((h-h_i)/d_i)}{1 + \exp((h_0-h_i)/d_i)}$$

$$m_i = \left(\frac{dT}{dh}\right)_{i-1,i} = \frac{T(h_i) - T(h_{i-1})}{h_i - h_{i-1}}$$

Global models for F2 peak (*fo*F2, *Nm*F2)





CCIR-65 (recommended in IRI to use of the continents):

Jones, W. B., & Gallet, R. M., Representation of diurnal and geographical variations of ionospheric data by numerical methods. *J. Res. National Bureau of Standards*, Section D: Radio Propagation, 66(4), 129–147,1962.

Jones, W. B., & Gallet, R. M. (1965). Representation of diurnal and geographic variations of ionospheric data by numerical methods, II. Control of instability. *ITU Telecommunication Journal*, 32(1), 18–28, 1965.

URSI-88 (the IRI default and strongly recommended over the oceans):

Rush C., M. Fox, D. Bilitza, K. Davies, L. McNamara, F. Stewart, and M. PoKempner, Ionospheric mapping – an update of foF2 coefficients, Telecomm J. **56**, 179 - 182, 1989.

Damboldt and Suessmann (2012) validation of IRI *fo*F2 with a large volume of ionosonde data over 7 solar cycles finds average error of just a few %.

CCIR (1967) global model for foF2

Jones and Gallet 1962
Jones *et al*., 1969

Ionosonde 1954–1958
plus screen points in ocean areas

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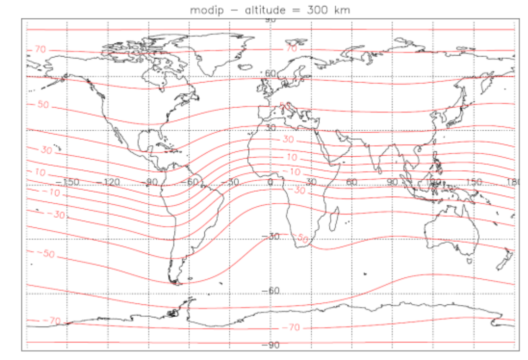
of the
International **T**elecommunication **U**nion

..using a special coordinate:
modified dip latitude



Ionospheric characteristics

1 Introduction

Expressions are provided for the evaluation of the monthly median of foF2, M(3000)F2, foE, foF1, h'F and h'F,F2 and of the monthly median, upper decile and lower decile of foEs and fbEs. Also included are representations of the percentage of occurrence of spread-F. These formulations yield values for any location, month and time-of-day for different solar epochs. In the case of foE and foF1, empirical formulae in terms of so… ionospheric characteristics a numerical mapping technique based on orthog…

Order 6 for foF2
Order 4 for M(3000)F2

2 Mapping functions

The general form of the numerical map function, $\Omega(\lambda, \theta, T)$ is the Fourier time series:

$$\Omega(\lambda, \theta, T) = a_0(\lambda, \theta) + \sum_{j=1}^{H} \left[a_j(\lambda, \theta) \cos jT + b_j(\lambda, \theta) \sin jT\right] \quad (1)$$

where:

- Ω: ionospheric characteristic to be mapped
- λ: geographic latitude ($-90° \leq \lambda \leq 90°$)
- θ: east geographic longitude ($0° \leq \theta \leq 360°$) (θ in degrees East of the Greenwich meridian)
- T: universal time (UTC) expressed as an angle ($-180° \leq T \leq 180°$)
- H: maximum number of harmonics used to represent the diurnal variation.

The Fourier coefficients, $a_j(\lambda, \theta)$ and $b_j(\lambda, \theta)$, vary with the geographic coordinates, and are represented by series of the form:

$$a_j(\lambda, \theta) = \sum_{k=0}^{K} U_{2j,k}\, G_k(\lambda, \theta), \quad j = 0, 1, 2, \ldots, H \quad (2a)$$

$$b_j(\lambda, \theta) = \sum_{k=0}^{K} U_{2j-1,k}\, G_k(\lambda, \theta), \quad j = 1, 2, \ldots, H \quad (2b)$$

The particular choice of the functions, $G_k(\lambda, \theta)$ is determined by specifying the integers k ($k_0, k_1, k_2, \ldots, k_i, \ldots, k_m$; $k_m = K$), where i is the order in longitude. Therefore, a numerical map can be written more explicitly in the form:

$$\Omega(\lambda, \theta, T) = \sum_{k=0}^{K} U_{0k}\, G_k(\lambda, \theta) + \sum_{j=1}^{H} \left[\cos jT \sum_{k=0}^{K} U_{2j,k}\, G_k(\lambda, \theta) + \sin jT \sum_{k=0}^{K} U_{2j-1,k}\, G_k(\lambda, \theta)\right] \quad (3)$$

$U_{2j,k}$ and $U_{2j-1,k}$ in equations (2a), (2b) and (3), can be written as $U_{s,k}$, where s is either $2j$ or $2j - 1$.

In the numerical mapping technique, the modified magnetic dip:

$$X = \arctan\left(\frac{I}{\sqrt{\cos \lambda}}\right) \quad (4)$$

has been used, where I is the magnetic dip and λ is the geographic latitude. Since X is a function of both geographic latitude and longitude, the formal expression of $\Omega(\lambda, \theta, T)$, equation (3), is unchanged. Table 1 shows the geographic functions, $G_k(\lambda, \theta)$.

… and a special set of geographic coordinate functions

76 coefficients for foF2
49 coefficinets for M(3000)F2

TABLE 1

Geographic coordinate functions $G_k(\lambda, \theta)$

(X is a function of λ and θ, m is the maximum order in longitude)

$$q_0 = k_0;\ q_i\ (i = 1, m) = \frac{k_i - k_{i-1} - 2}{2}$$

k	Main latitude variation	k	First order longitude	k	Second order longitude	. . .	k	mth order longitude
0	1	$k_0 + 1$	$\cos\lambda \cos\theta$	$k_1 + 1$	$\cos^2\lambda \cos 2\theta$	. . .	$k_{m-1} + 1$	$\cos^m\lambda \cos m\theta$
1	$\sin X$	$k_0 + 2$	$\cos\lambda \sin\theta$	$k_1 + 2$	$\cos^2\lambda \sin 2\theta$	. . .	$k_{m-1} + 2$	$\cos^m\lambda \sin m\theta$
2	$\sin^2 X$	$k_0 + 3$	$\sin X \cos\lambda \cos\theta$	$k_1 + 3$	$\sin X \cos^2\lambda \cos 2\theta$	. . .	$k_{m-1} + 3$	$\sin X \cos^m\lambda \cos m\theta$
.		$k_0 + 4$	$\sin X \cos\lambda \sin\theta$	$k_1 + 4$	$\sin X \cos^2\lambda \sin 2\theta$	. . .	$k_{m-1} + 4$	$\sin X \cos^m\lambda \sin m\theta$
. . .		. . .		. . .			. . .	
k_0	$\sin^{q_0} X$	$k_1 - 1$	$\sin^{q_1} X \cos\lambda \cos\theta$	$k_2 - 1$	$\sin^{q_2} X \cos^2\lambda \cos 2\theta$	. . .	$k_m - 1$	$\sin^{q_m} X \cos^m\lambda \cos m\theta$
		k_1	$\sin^{q_1} X \cos\lambda \sin\theta$	k_2	$\sin^{q_2} X \cos^2\lambda \sin 2\theta$	. . .	k_m	$\sin^{q_m} X \cos^m\lambda \sin m\theta$

CCIR 1967	URSI 1988
Jones and Gallet, 1962 Jones *et al*., 1969	Fox and McNamara,1988 Rush *et al.*,1989
Ionosondes 1954-1958	45,000 station months of ionosonde data
Screen points, especially over the oceans and southern hemisphere, through extrapolation along lines of constant modified magnetic dip angle	Theoretical model was adjusted such that it agreed with measured *foF2* values over land, and then was used to compute screen points over oceans and in data sparse regions
6th order harmonics in UT and special functions for global specification	Same functions as CCIR
Recommended over continents	Recommended over ocean areas

Room for improvement: Large volume of more recent data, better models for screen point analysis, better functions, better computers

IRI Drivers – Indices used

Electron Density (N_e)	D-Region	Bilitza, 1981	R12
		Friedrich et al., 2018	F10.7D
		Danilov et al., 1995	F10.7D, K_p
	E-Peak	Kouris & Muggleton, 1973	COV
		Mertens et al., 2013	a_p
	F1-Region	Ducharme et al. 1973	R12
		Scotto et al. 1997	R12
	Bottom--side	Bilitza et al., 2000	R12
		Altadill et al. 2009	R12
	F-Peak	Jones&Gallet, 1965	IG12
		Rush et al., 1989	IG12
		Fuller-Rowell et al., 2000	a_p*
	hmF2	Bilitza et al. 1979	R12
		Altadill et al. 2013	R12
		Shubin 2015	F10.7_81
	Topside	Rawer et al. 1978	COVSAT
		Nava et al. 2008	R12
		Bilitza & Xiong, 2021	PF10.7
	Spread-F	Abdu et al. 2003	F10.7D
Temperatures (T_e, T_i, T_n)	T_e , T_i	Truhlik et al. 2011, 2021	PF10.7
	T_n CIRA	Picone et al. 2002	F10.7_81o, F10.7DPo
Ion composition and velocity (N_i, v_i)	N_i(h ≤ 300km)	Richards et al. 2010	F10.7_81o, F10.7DPo
	N_i(h > 300km)	Triskova et al. 2003	PF10.7
	N_i(h ≤ 300km)	Danilov&Smirnova 95	F10.7_12
	N_i(h > 300km)	Danilov&Yaichnikov 85	F10.7_12
	v_i	Fejer et al. 2007	F10.7D
Auroral Boundary		Zhang et al., 2010	K_p

R12 = 12-month running mean of sunspot number

F10.7D = daily F10.7 index (adjusted to AU)

F10.7DP = daily F10.7 index of previous day

F10.7DPo = F10.7DP observed

F10.7_81 = 81-day running mean of F10.7

F10.7_12 = 12-month running mean of F10.7

PF10.7 = (F10.7_81 + F10.7D)/2

COV= F10.7_365

COVSAT= COV if(COV.gt.188.) COVSAT=188

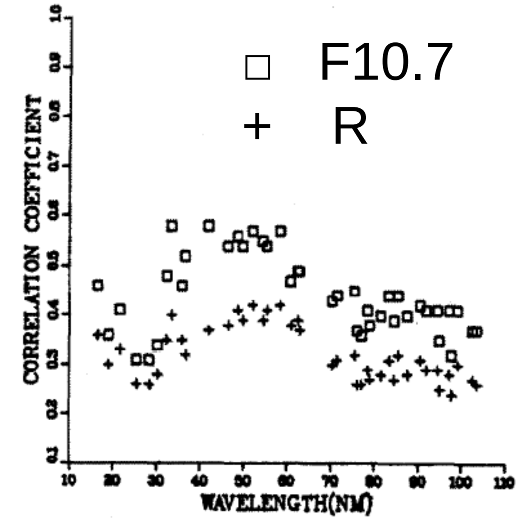
IG = Global Ionospheric index

IG12 = 12-month running mean of IG

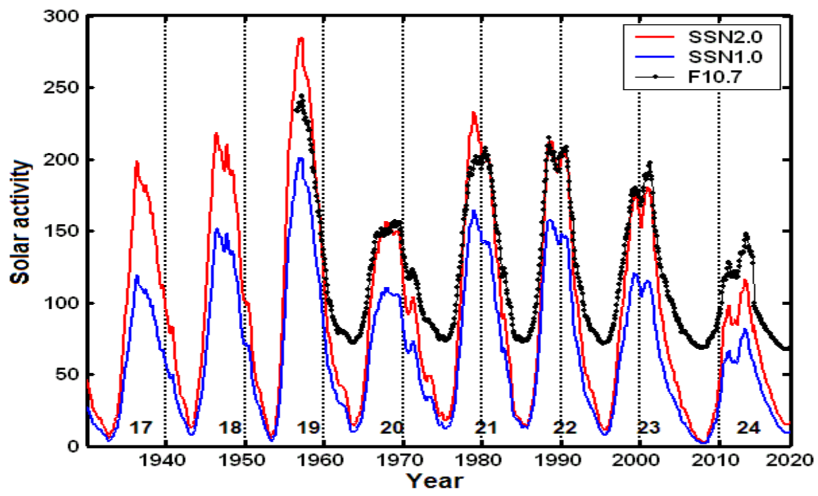
*a_p = 3-hr a_p index for current time and the 12 preceding 3-hr ap indices

Problems with solar indices R and F10.7

R is related to the number spots observed in sun's photosphere. F10.7 is related to the solar irradiance at 10.7cm wavelength while the irradiance responsible for ionospheric ionization is in the range 1-120nm (X-ray to EUV).



Correlation between F10.7 (R) and EUV fluxes measured by the EUV spectrometer on the AEROS-A satellite at different wavelengths.



R was recently significantly revised; a factor ~1.5 increase (Clette et al., SW, 2015). Since the IRI models were developed with the 'old' R12 we use a scale factor of 0.7 with the new R12.

Solar indices describe only solar influence (ionization) not dynamics of F region. Good in solar-controlled E and F1 region.

1-2 day delay between solar irradiance and ionospheric response

Ionosonde Index IG

Based on work of Liu et al., *Telecomm. J.*, 1988:

- Using noontime measurements of *foF2* from 13 globally distributed ionosondes.
- Is obtained by adjusting R_{12} in the CCIR-*foF2* model until agreement is achieved between ionosonde data and model.
- Then taking the median of the 13 adjusted R_{12} values.

Problems:

- Stations have varied over time and the original 13 are now down to 4 (Chilton, Port Stanley, Kokubunji, and Canberra).
- There is an IG_{CCIR} index but not an equivalent IG_{URSI} index.
- Only noon time data are being used.
- Ionosonde indices work best locally or regionally; averaging over too wide a latitude range greatly diminishes the usefulness of these indices.

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IRI Improvements

- **New data and better data averaging/fitting methods and functions**
- **More accurate description of the driver-parameter relationship**
  - IRI uses 13-month running means of R and IG for F-peak and other parameters
  - The sunspot number index R was recently significantly revised; a factor 1.4 increase (Clette et al., SW, 2015).
  - The ionosonde-based IG is better than EUV indices because it includes dynamical effects; EUV indices are better than R and F10.7 because the ionospheric plasma is created by EUV radiation.
  - Time delays of 1-3 days need to be considered when using solar indices.
- **Updating IRI with real-time or retrospective data**
  - IRI allows input of NmF2/foF2, hmF2, NmF1/foF1, NmE/foE, hmE, B0, B1 if appropriate measurements are available.
  - Equivalent R and/or IG are obtained by adjusting IRI output with F-peak measurements and/or TEC.
- **Assimilating real-time or retrospective data into IRI**
  - IRTAM: Real-time global digisonde data for foF2, hmF2, B0, and B1
  - Various techniques for assimilating foF2 and TEC data into IRI.

Advantage of Empirical Models

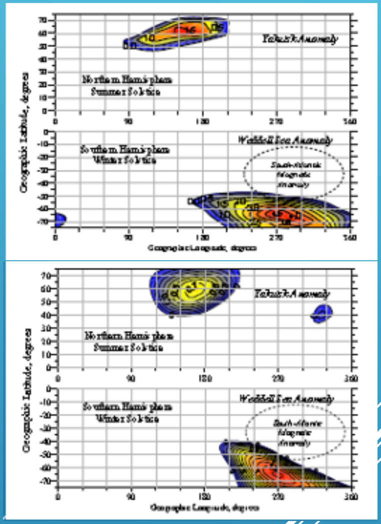
Being an empirical model IRI has the advantage that it already included some of the newly discovered phenomena that theoretical modelers still need to investigate and fully include in their modeling framework.

$foF2_{midnight} – foF2_{noon}$

Weddell Sea and Yakutsk Anomalies: *foF2* in summer larger during nighttime than during daytime. The meridional component of the neutral wind reaches maximum values at the anomaly sites (during summer nights) because of the combined effect of solar EUV heating (sunlit magnetic pole in summer) and heating from precipitating auroral electrons.

IK-19

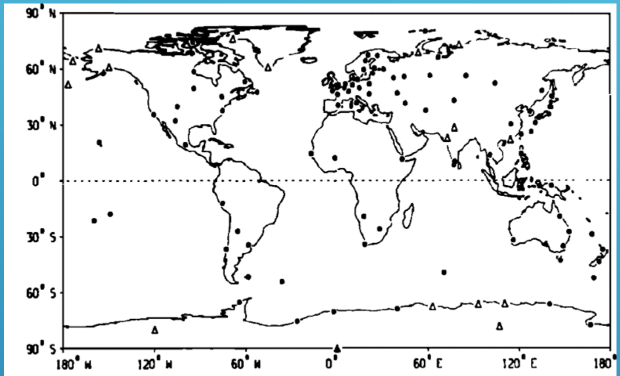
IRI



Longitudinal 4-peak wave pattern near the magnetic equator: First observed with IMAGE/EUV and then confirmed with data from CHAMP, TOPEX and TIMED/GUVI. This phenomena is thought to being caused by non-migrating diurnal atmospheric tides that are, in turn, driven mainly by weather in the tropics.

Disadvantage of Empirical Models

Only as good as the data base available for its development.

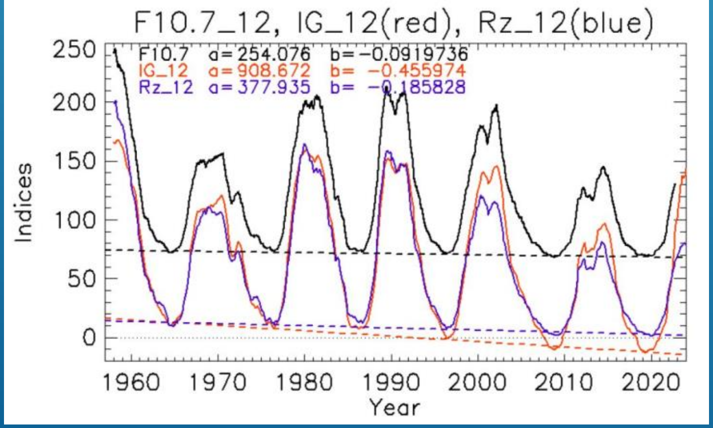


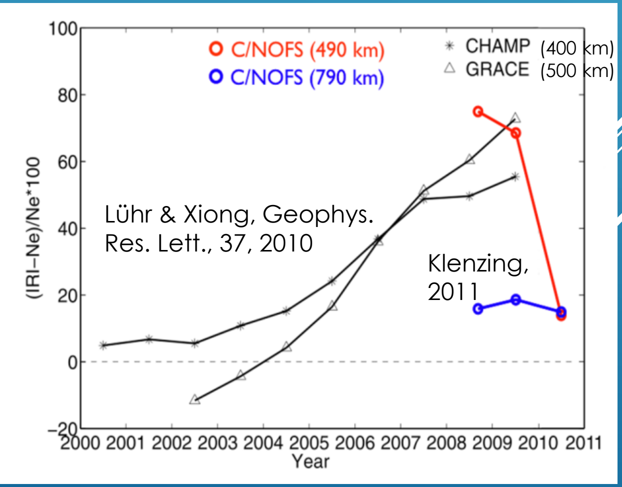
Bias towards Northern mid-latitudes due to global ground stations distribution.

~1962 Ionosondes

2012 digisondes

Recent very low and broad solar minima brought conditions not covered by data available from previous solar minima leading to overestimations by the model.





IRI Real-Time Algorithms

- ADJUSTING IRI DRIVERS (INDICES) UNTIL IRI AGREES WITH OBSERVATIONS
- ASSIMILATING REAL-TIME DATA INTO BACKGROUND IRI
- BOTH TECHNIQUES CAN BE USED ALSO FOR RETROSPECTIVE ANALYSIS
- FORECAST REQUIRES INDICES FORECAST

Adjusting IRI Drivers (Indices)

Indices used to drive the IRI model:

- Solar indices: F10.7 (daily, 81-day, 365-day), R (12-month running mean)
- Ionospheric (ionosonde) index: IG (12 month running mean)
- Magnetic indices: ap and kp (3-hour, daily)

Updating algorithms using effective indices:

- Bilitza et al. (1997) - Effective **IG12** index (**EIG12**) determined with ionosonde *foF2* data
- Komjathy et al. (1998),– **EIG12** with GPS *vTEC* map
- Hernandez-Pajares et al. (2002) - **EIG12** with GPS slant *TEC*
- Zhang et al. (2010) – **Effective Kp** from GUVI/SSUSI for auroral boundary model
- Pezzopane et al. (2011) – **EIG12** from ionosondes plus assimilation of bottomside profiles
- Migoya-Orué et al. (2015) – **EIG12** with GIM and using interpolation within a grid
- Ssessanga et al. (2015) – Regional IRI update with **EIG12** from South-Korean *TEC* data
- Habarulema and Ssessanga (2016) - **ER12** and **EIG12** for IRI with African *TEC* data
- Pignalberi et al. (2018) - **ER12** and **EIG12** grid from ionosonde data and Kriging method
- Brown et al. (2018) – Hemispheric monthly **EIG** indices from ionosonde *foF2*
- Pignalberi et al. (2019) – Updated their method with **ER12/EIG12** to also rely on *vTEC* data

Assimilating Data into IRI

Direct input into IRI model:

- Observations of *foF2*/*NmF2*, *hmF2*/*M(3000)F2*, *foF1*/*NmF1*, *foE*/*NmE*, *hmE*, *B0*, *B1*

Assimilation of GNSS TEC data into IRI:

- Schmidt et al. (2008), Weijing et al. (2015) - Multi-dimensional B-spline with GNSS and TOPEX/Jason
- Fridman et al. (2006) – GPSII, Tikhonov method with GPS data
- Angling et al. (2009) - EDAM assimilates GPS data with a minimum variance estimation technique
- An et al. (2019) - Assimilating Jason-2/-3 and > 300 GNSS stations from 2014 and 2018 using a two-dimensional spherical harmonic expansion in a sun-fixed geomagnetic reference frame.

Assimilation of ionosonde data into IRI:

- Galkin et al. (2012, 2020),– IRI Real-Time Assimilative Mapping (IRTAM): Assimilative Mapping with GIRO ionosonde data using CCIR formalism for data-model difference maps and NECTAR model morphing algorithm.

Assimilation of a combination of different data sources:

- Yue et al. (2012) – Assimilating GPS and Jason 1,2 vTEC, and Radio Occultation (RO) from CHAMP, GRACE, COSMIC, SAC-C, Metop-A, and TerraSAR-X with the Kalman filter technique for 2002-2011.
- Aa et al. (2016) – Regional model using 3-dimensional variational technique to assimilate GNSS data from Chinese and International networks, and COSMIC RO data.
- Lin et al. (2017) – Gauss-Markov Kalman filter assimilation of GPS and RO data into IRI.
- Mengist et al. (2019) – Assimilating GNSS and COSMIC RO data into IRI using a 3D-Var Algorithm (IDA4D) for a regional model.

New in IRI-2020

- **D-Region:** An updated model for the D-region electron density based on a simple ion-chemical model that is corrected with radio propagation data from 327 rocket fights (*Friedrich, M., et al. JGR 123(8) 6737-6751, 2018*).
- **Topside:** Improved representation during low solar activity based on Alouette, ISIS, CHAMP, Grace, and Swarm data (*Bilitza, D. & Xiong, C., Adv. Space Res., 68(5), 2124-2137, 2021*).
- **Ion temperature:** New model based on in-situ observations from 18 satellites inter-calibrated with ISR data and consisting of global maps at 350, 430, 600, and 850 km (*Truhlik, V. et al., MDPI Atmosphere, 12(8), 1081, 2021)*
- **Ion drift:** Equatorial vertical ion drift model based on 5 years of ROCSAT-1 measurements using an interpolation scheme between grid points in altitude, longitude, local time, season and solar activity (*Fejer et al., JGR, 113, 2008)*
- **New Default:** IRI-2016 introduced two new options for ***hmF2*** the digisonde-based model of Altadill et al. (2015) and the COSMIC-RO-based model of Shubin (2015) and recommended the first as the default model. Based on the results from several recent studies comparing the models to additional data the recommended default was changed to the Shubin model.
- **Plasmasphere extension:** Using the model of Gallagher et al. (2000) or the Ozhogin et al. (2012) model at selected fixpoints and using the Booker approach to connect thee fixpoints with the topside profile
- **F1 layer:** Option of a strict omission of the **F1** feature independent of the IRI-estimated probability. This was added because of the disruptive effect the on-off transition can have on applications that require a continuous varying electron density profile.

IRI - Future Plans

- ***Real-Time IRI:*** Collaboration with IGS Iono group to make use of the ever improving global vTEC representation for adjusting the IRI topside electron densities to real-time conditions.
- ***Sporadic-E****:* Develop a global model of the occurrence probability of Sporadic-E based on COSMIC I and II data
- ***Scintillation/Spread-F/Bubbles:*** Occurrence probability of scintillations, spread-F and equatorial bubble activity based on COSMIC and other data
- ***foF2:*** Include the model developed by Shubin and Deminov (2019) based on ionosonde and radio occultation data as a new option for the representation of the F2 peak plasma frequency including storm effects and main ionospheric trough
- ***hmF2:*** Representation of the effects of ionospheric storms on F2 peak height based on the work of Blanch & Altadill (2012); requires solar wind input (IMF-B_z).

IRI Working Group Members (67/29)

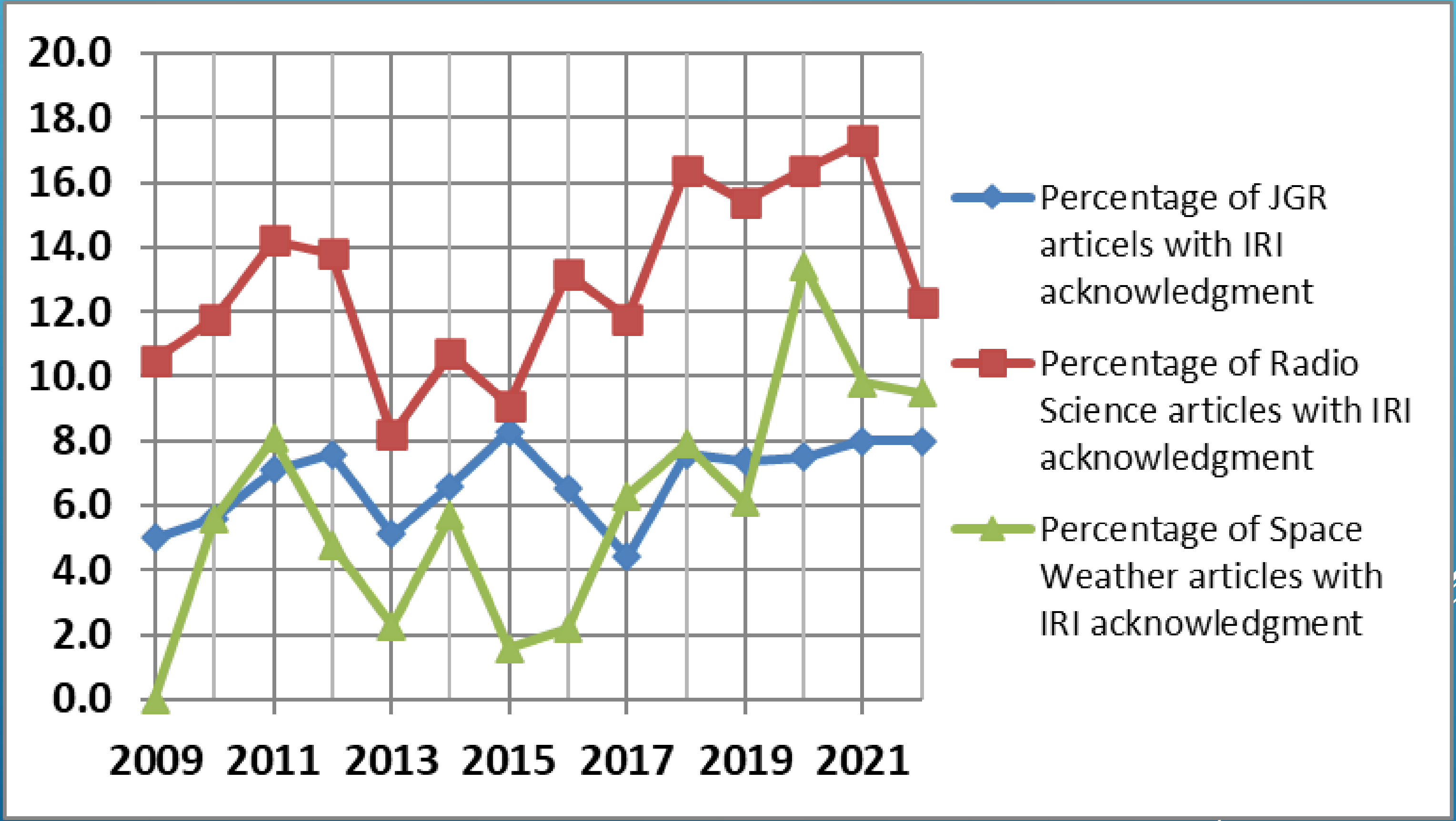
IRI team's global distribution guarantees access to the global data base

IRI Workshops and Publications

2017	**IRI CCBW** NCU, Taiwan	**Real-time Ionospheric Predictions with IRI and COSMIC and other GNSS Data**	 ***Advances in Space Research*** **Vol 63, No 6, 2019**
2018	**COSPAR** General Assembly	**Description of the Ionosphere through Data Assimilation**	**Pasadena, California, USA** **July 14-22, 2018**
2019	**IRI CCBW** Frederick University Nicosia, Cyprus	**Real-time ionospheric modeling in the European and African sector**	 ***Advances in Space Research*** **Vol 68, No 5, 2021**
2021	**COSPAR** General Assembly	**Improving the Description of Hemispheric Differences in Ionospheric Models**	**Sydney, Australia** **Online, Jan 25- Feb 4, 2021**
2021	**URSI** General Assembly	**IRI: Progress in Retrospective and Real-Time Ionospheric Predictions**	**Rome, Italy** **Hybrid, Aug 28- Sep 4, 2021**
2022	**COSPAR** General Assembly	**Real-time and retrospective ionospheric modelling with in-situ and GNSS data**	**Athens, Greece** **Hybrid, July 16 - 24, 2022**
2023	**IRI CCBW**	**Improved Real-time IRI Predictions with data from spaceborne sensors and GNSS**	**Daejeon, South Korea** **May 8-19 2023**
2023	**URSI** General Assembly	**International Reference Ionosphere: Improvement, Validation and Usage**	**Sapporo, Japan** **August 19 - 26, 2023**
2024	**COSPAR** General Assembly	**International Reference Ionosphere: Improvements, Validation and Applications**	**Busan, South Korea** **July 13 - 21, 2024**

IRI Usage in AGU Journals

Percentage of papers per year that acknowledge usage of the IRI model in the AGU journals *Journal of Geophysical Research*, *Radio Science*, *and Space Weather* for the years 2009 to 2022.



IRI highly cited in wide range of journals

About 200 citations per year in many different journals (36):

Advances in Space Research	Advances in Radio Science
Annales Geophysicae	Applied Optics
Astrophysics and Space Science	MDPI Atmospheres
Chinese Journal of Aeronautica	Computer Physics Communications
Computers & Geosciences	Cosmic Research
Earth, Planets and Space	Frontiers Astronomy & Space Science
Geochimica et Cosmochimica Acta	Geodesy and Geodynamics
Geophysical Research Letters	Geomagnetism and Aeronomy
GPS Solutions	IEEE Access
IEEE Trans. Geosci. & Remote Sensing	Journal of Asian Earth Science
Journal of Atmos. Solar-Terr. Physics	Journal of Geodesy
Journal of Geophysical Research	Journal of Geospatial Information Technology
J. Machinery Manufact.&Reliability Metrics	Journal Space Weather & Space Climate
Navigation	Planetary and Space Science
Plasma Science and Technology	Radio Science
MDPI Remote Sensing	Results in Physics
Solar Physics	Space Science Review
Space Weather	Surveys in Geophysics

The 2017 IRI paper was the most cited paper in AGU's Space Weather journal

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2022RG000792

The International Reference Ionosphere Model: A Review and Description of an Ionospheric Benchmark

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Key Points:

- International Reference Ionosphere (IRI): Scientific background and mathematical formalism
- Description of the latest version of the model: IRI-2022
- IRI Achievements and plans for the future

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Author Contributions:

Abstract This paper is a review of the International Reference Ionosphere (IRI) project and model. IRI is recognized as the official standard for the Earth's ionosphere by the International Standardization Organization, the International Union of Radio Science, the Committee on Space Research, and the European Cooperation for Space Standardization. As requested by these organizations, IRI is an empirical (data-based) model representing the primary ionospheric parameters based on the long data record that exists from ground and space observations of the ionosphere. The core model describes monthly averages of the electron density, electron temperature, ion temperature, and ion composition globally in the altitude range from 60 to 2,000 km. Over time additional parameters were added in response to requests from the user community, this includes the equatorial ion drift, the occurrence probability of spread-F and of an F1 layer, auroral boundaries and the electron content from the bottom of the ionosphere to user-specified altitude. IRI has undergone extensive validations and is used for a wide range of applications in science, engineering, and education. This review is the result of many requests we have received for a comprehensive description of the model. It is also meant as a guide for users who are interested in a deeper understanding of the model architecture and its mathematical formalism.