Radio, Ionosphere, Magnetism, and Sunspots

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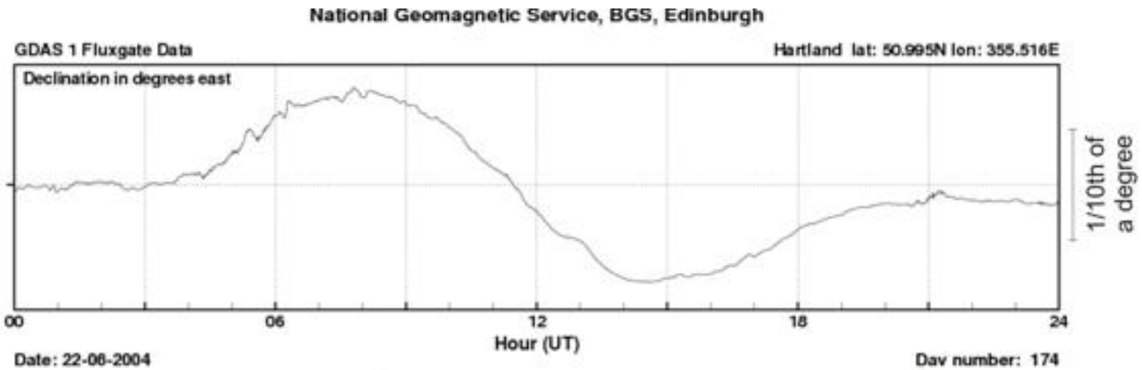
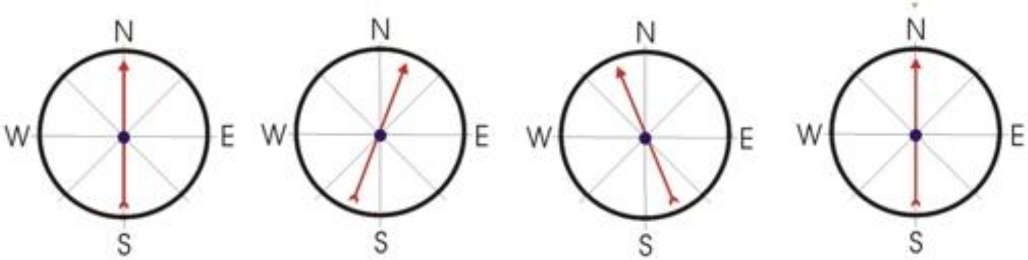
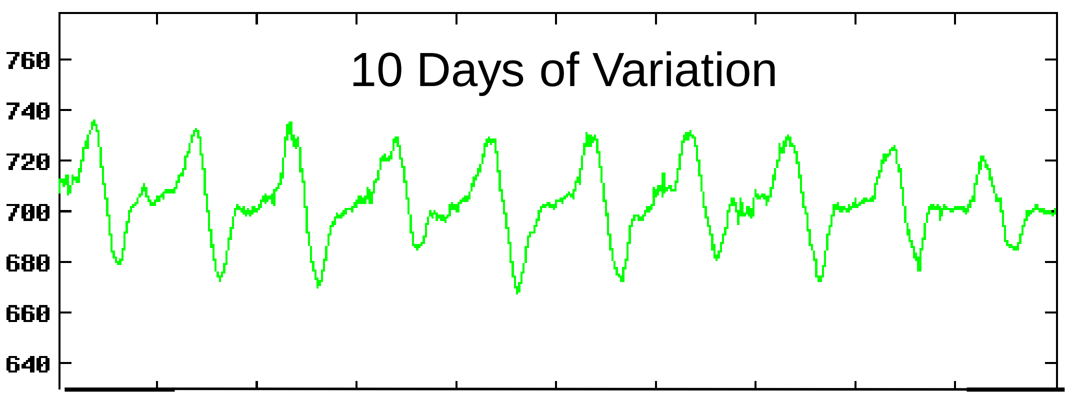
Stanford University

SARA 2015, March 22

The Diurnal Variation of the Direction of the Magnetic Needle

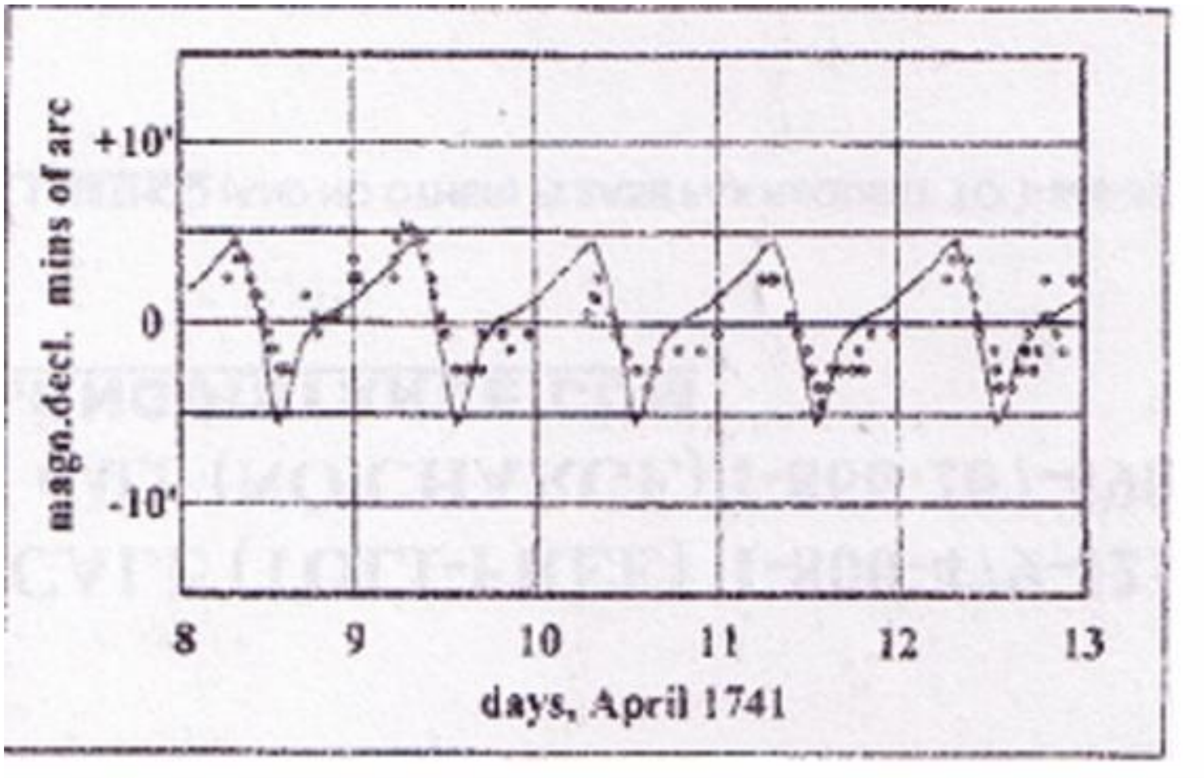






George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

Observations in the 1740s



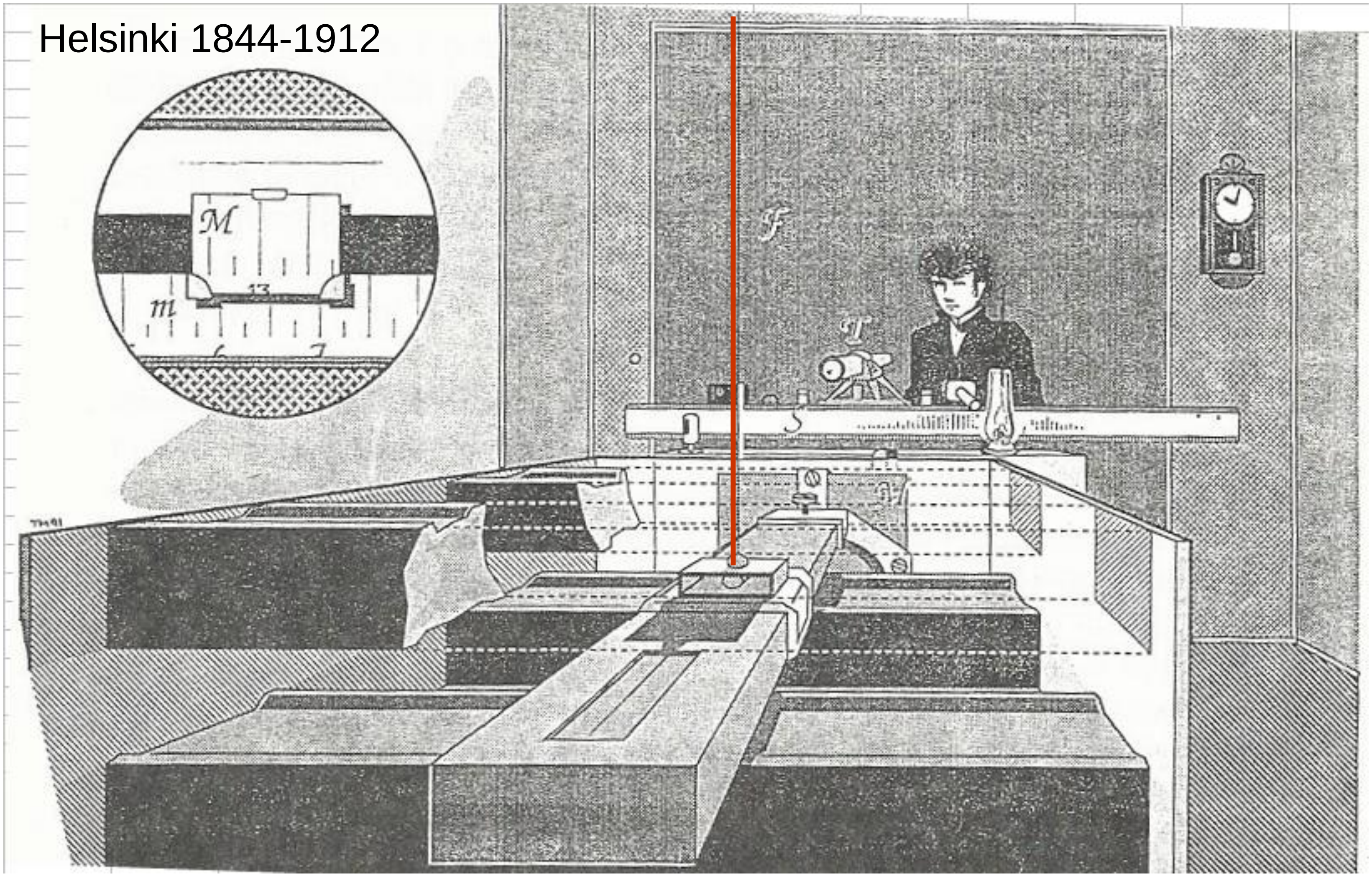
Olof Petrus Hjorter was married to Anders Celsius’ sister and made more than 10,000 observations of the magnetic declination in the 1740s.

Hjorter’s measurements of the magnetic declination at Uppsala during April 8-12, 1741 (old style). The curve shows the average variation of the magnetic declination during April 1997 at nearby Lovö (Sweden).

Even Rather Simple Instruments Could Readily Show the Variation

John Canton [1759] made ~4000 observations of the Declination on 603 days

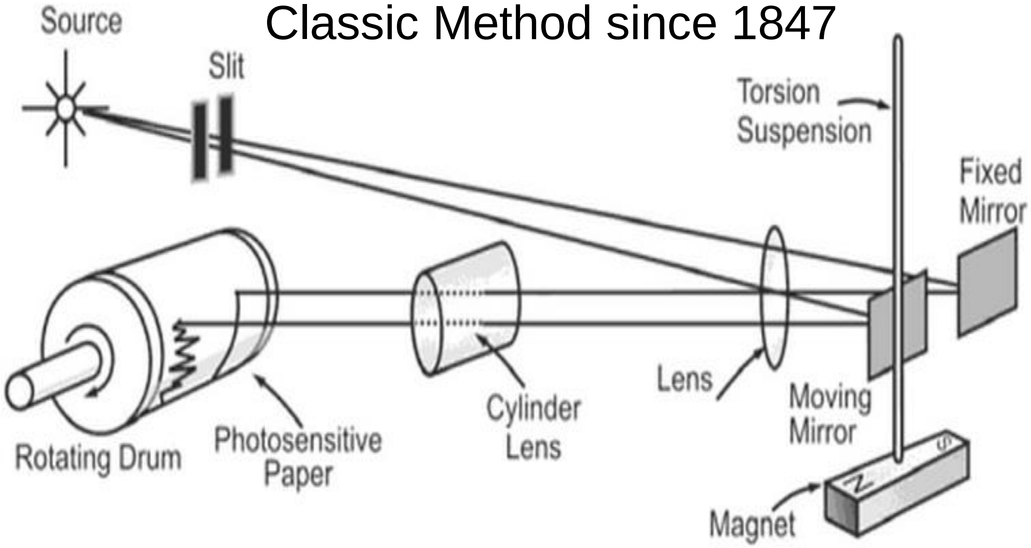
Variometer Invented by Gauss, 1833

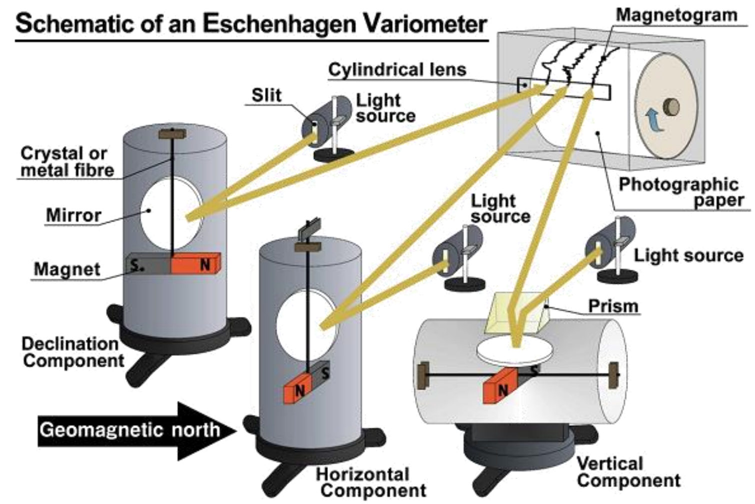


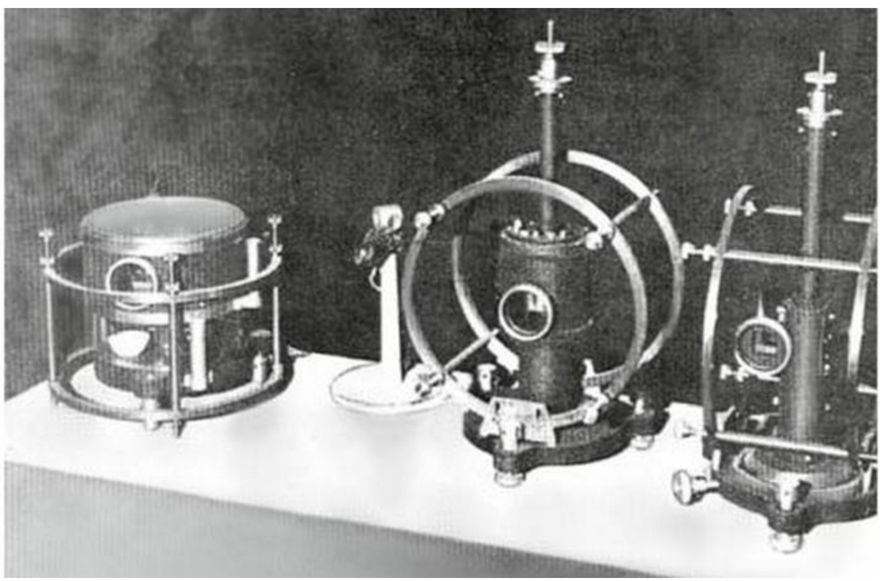
Nevanlinna et al.

Magnetic Recorders

Classic Method since 1847





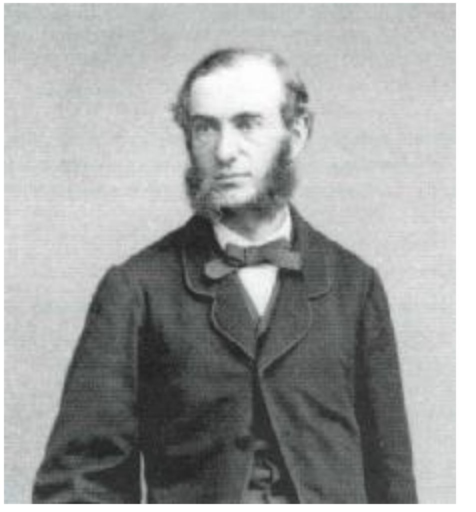


Classic Instruments circa 1900

Modern Instrument

Balfour Stewart, 1882, Encyclopedia Britannica, 9th Ed.

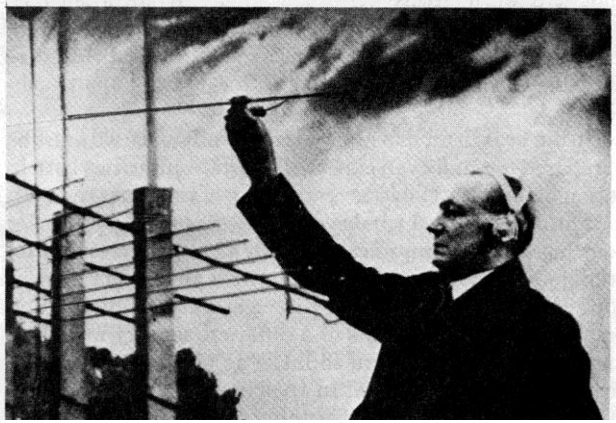
"The various speculations on the cause of these phenomena [daily variation of the geomagnetic field have ranged over the whole field of likely explanations. (1) […], (2) It has been imagined that convection currents established by the sun's heating influence in the **upper regions of the atmosphere are to be regarded as conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet**, (3) […], (4) […].



Balfour Stewart
1828-1887

"there seems to be grounds for imagining that their **conductivity may be much greater than has hitherto been supposed**."

We all Know about Marconi's Long-Distance Radio Transmissions



Guglielmo Marconi sends message from England to Newfoundland

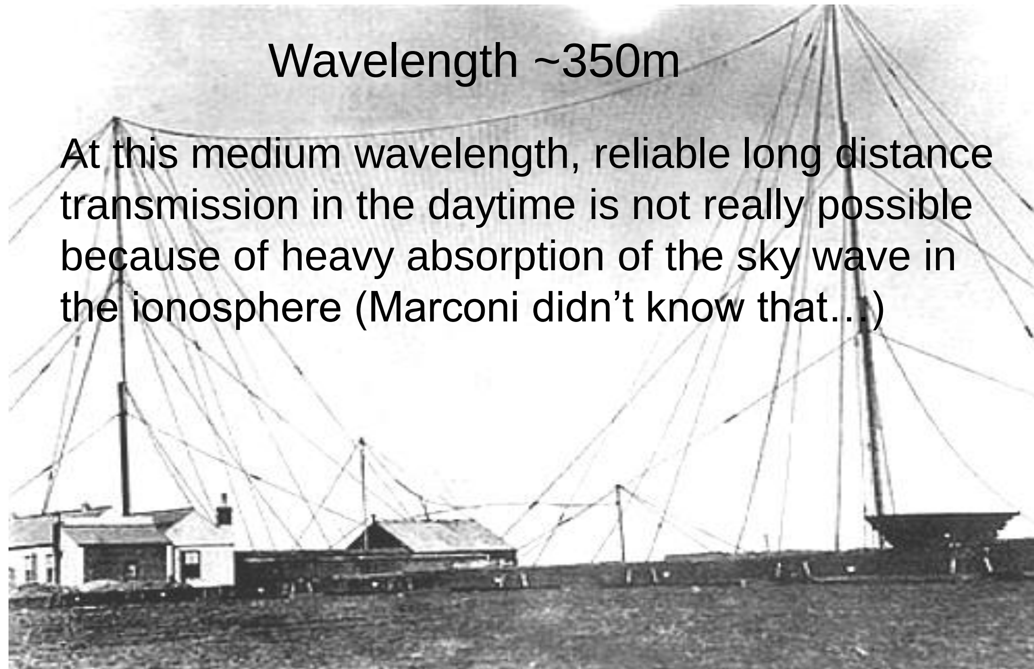
Dec 12. The Italian physicist Guglielmo Marconi, who sent wireless telegraphic messages across the English Channel from Dover, England, to Boulogne, France, on March 29, 1899, repeated his experiment today over the Atlantic Ocean, a distance of 2,232 miles.

In order to carry out this experiment, Marconi set up a 164-foot-high antenna in Poldhu, Cornwall, England. Then, he erected a receiver in St. John's, Newfoundland, Canada. In spite of the earth's curvature, he received a Morse signal corresponding to the letter "S" from the Poldhu station across the ocean.

When Marconi realized the importance of his first discoveries in 1895, he asked the Italian Minister of Telecommunication to help him. But the minister found that Marconi's experiments were too extravagant. That's why Marconi went to England, where he won the support of Sir William Peace, the Postmaster General, who immediately understood the significance of the young Marconi's work. Thanks to Peace's perspicacity and the help of Professor Adolf Slaby, Marconi could hit his target today (→ 2/22/03).

Guglielmo Marconi and his first wireless.

Dec. 12, 1901



Wavelength ~350m

At this medium wavelength, reliable long distance transmission in the daytime is not really possible because of heavy absorption of the sky wave in the ionosphere (Marconi didn't know that…)

Kennelly Suggested a Wave Guide

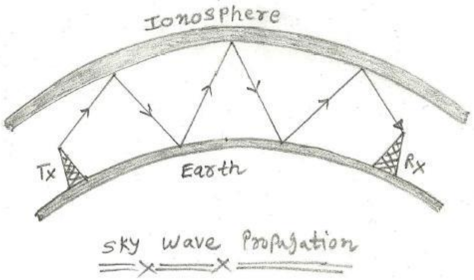
On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere.

By A. E. Kennelly.

There is well-known evidence that the waves of wireless telegraphy, propagated through the ether and atmosphere over the surface of the ocean, are reflected by that electrically-conducting surface. On waves that are transmitted but a few miles the upper conducting strata of the atmosphere may have but little influence. On waves that are transmitted, however, to distances that are large by comparison with 50 miles, it seems likely that the waves may also find an upper reflecting surface in the conducting rarefied strata of the air. It seems reasonable to infer that electromagnetic disturbances emitted from a wireless sending antennæ spread horizontally outwards, and also upwards, until the conducting strata of the atmosphere are encountered, after which the waves will move horizontally outwards in a 50-mile layer between the electrically-reflecting surface of the ocean beneath, and an electrically-reflecting surface, or successive series of surfaces, in the rarefied air above.

MARCH 15, 1902. ELECTRICAL WORLD AND ENGINEER. 473

Arthur E. Kennelly
1861-1939



Oliver Heaviside Got the Same Idea

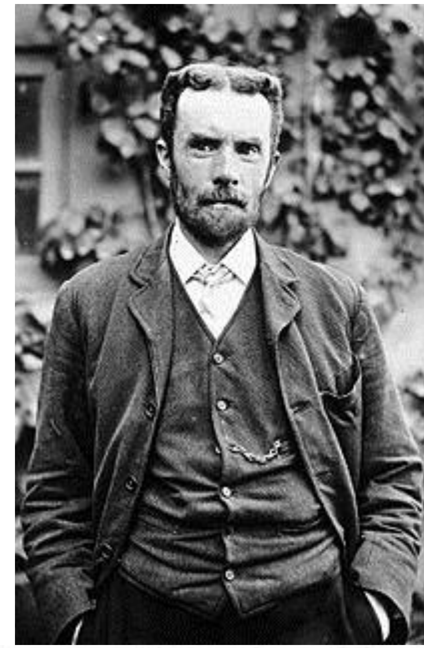
Marconi himself speculated that this might be the result of what he called the "diselectrification" of the antenna by daylight which prevented "the electrical oscillations [in the antenna] from acquiring so great an amplitude as they attain during darkness."

Heaviside proposed another possibility.

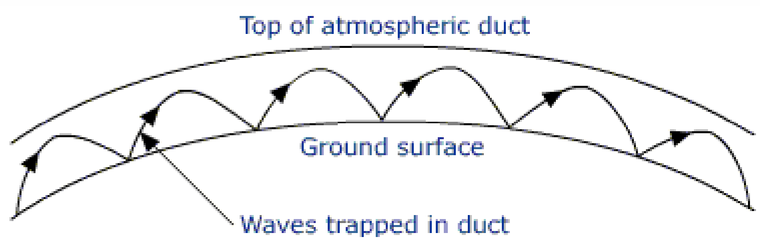
The actual correspondence is not available, but an account[56] has been given by Eccles[57]:

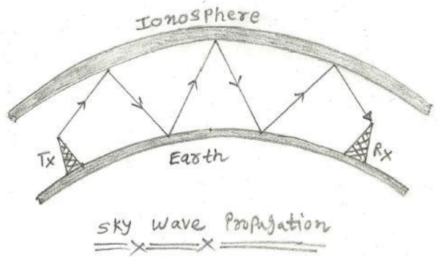
> In the spring of 1902 I was writing from time to time on wireless telegraphy in the pages of *The Electrician*, and one day Mr. Tremlett Carter, the editor, showed me a letter from Mr. Oliver Heaviside which, while discussing other things, asked if the recent success of Mr. Marconi in telegraphing from Cornwall to Newfoundland might not be due to the presence of a permanently conducting upper layer in the atmosphere. I believe this letter was shown to various friends of the editor, but I think it was not published [indeed, it was not].

Whatever the reason for the rejection of this letter for publication (I have been unable to find any reference to it in the surviving Heaviside editorial correspondence[58] with *The Electrician*), it merely made Oliver look for an alternative outlet. He found this outlet in the form of an invited contribution[59] to the new (10th) edition of the *Encyclopedia Britannica*.



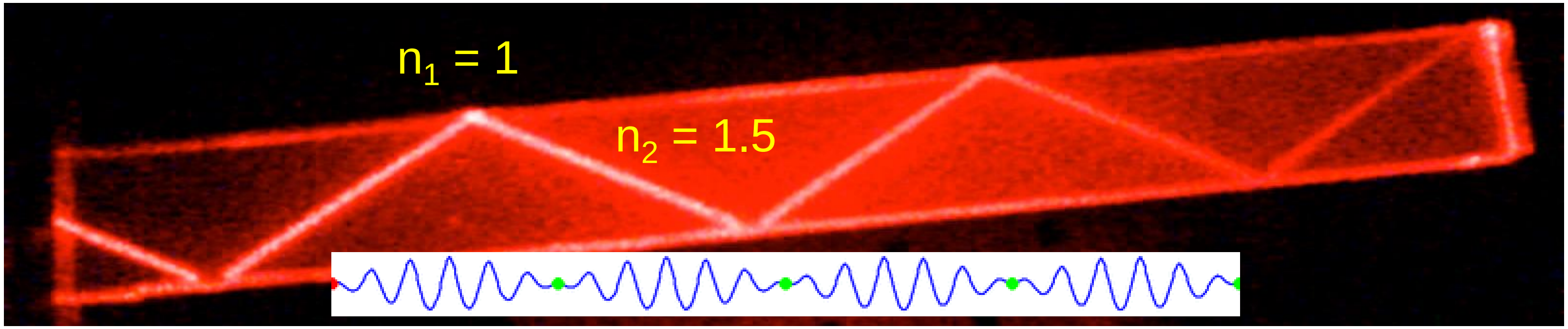
And then comes the *most* famous part of the article. "There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it more or less. Then the guidance will be by the sea on one side and the upper layer on the other."





A Reflection Problem

Total internal reflection happens when a wave hits a medium boundary at an angle larger than the so-called critical angle. If the refractive index is lower on the outer side of the boundary and the incident angle is greater than the critical angle the wave is reflected back. The refractive index, *n*, of a medium is the ratio between the speed of light in vacuum, *c*, and the speed of light, *v*, in the medium: $n = c/v$. To get total internal reflection from the ionosphere, the speed of light there must be significantly greater than that in air [which to 5 decimal places is the same as in vacuum], not to speak about the lower boundary... The solution to this problem was only found around 1910 by realizing that for the velocity in the medium we should use the *phase velocity* (red dot overtaking the green dot below), which does not transmit information and can easily be greater than *c.*



It Took These Gentlemen to Convincingly Establish the Ionosphere in the 1920s

Edward V. Appleton
1892-1965

Merle Antony Tuve
1901-1982

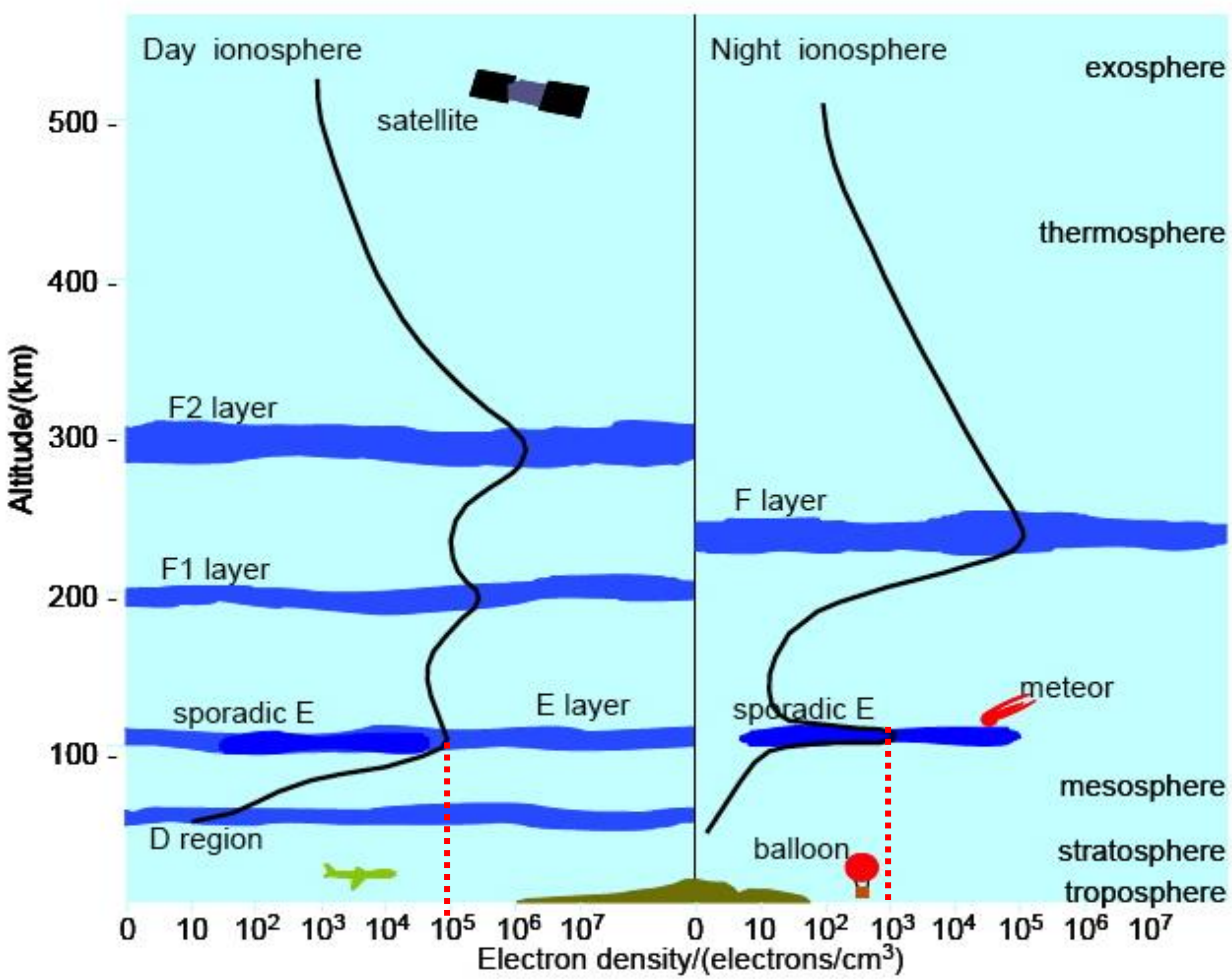
Grigory Breit
1899-1981

Discovered the F-layer higher up

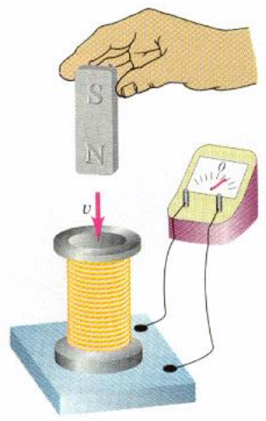
Used pulsed radio transmissions to determine the height of the ionosphere from timing the echoes

Nobel Prize 1947

Ionospheric Layers



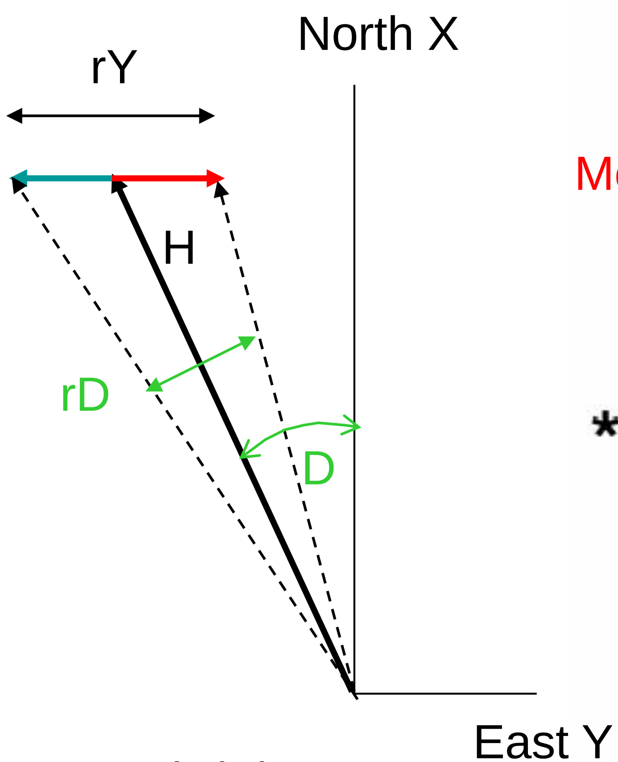
Dynamo

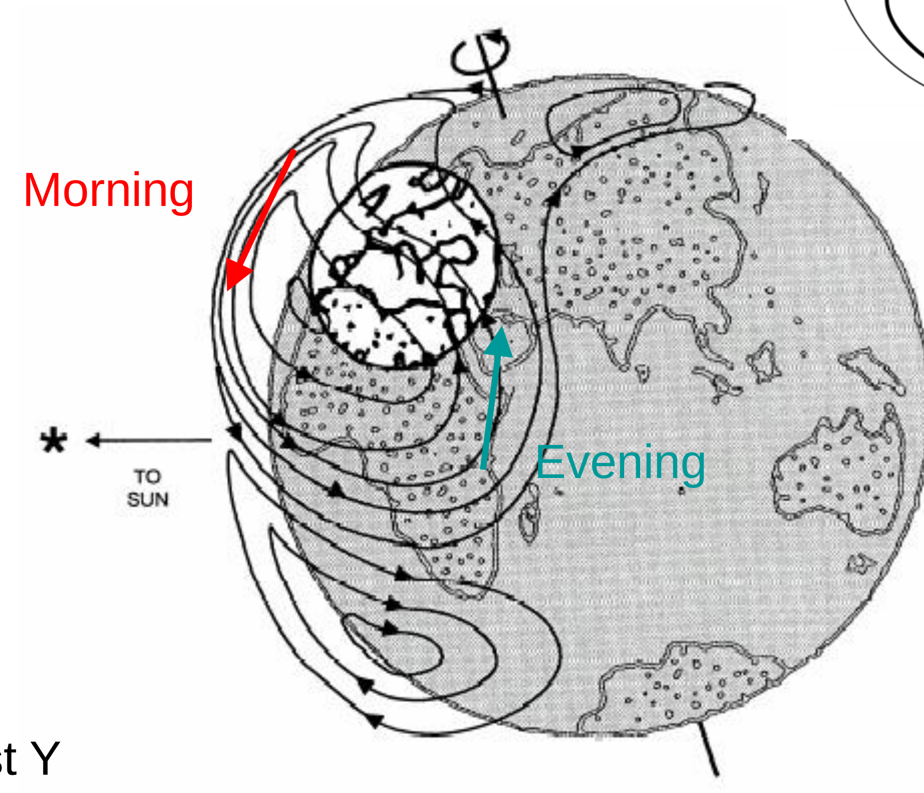


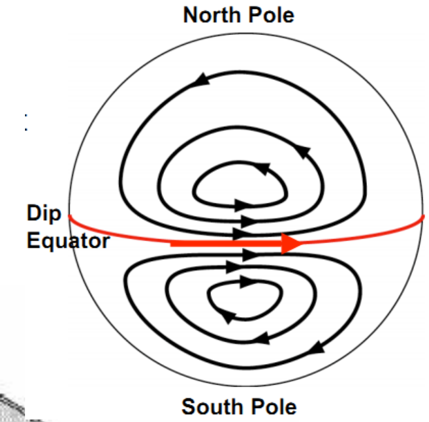
An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.

We thus expect the geomagnetic response due to electric currents induced in the E-layer.

The E-layer Current System







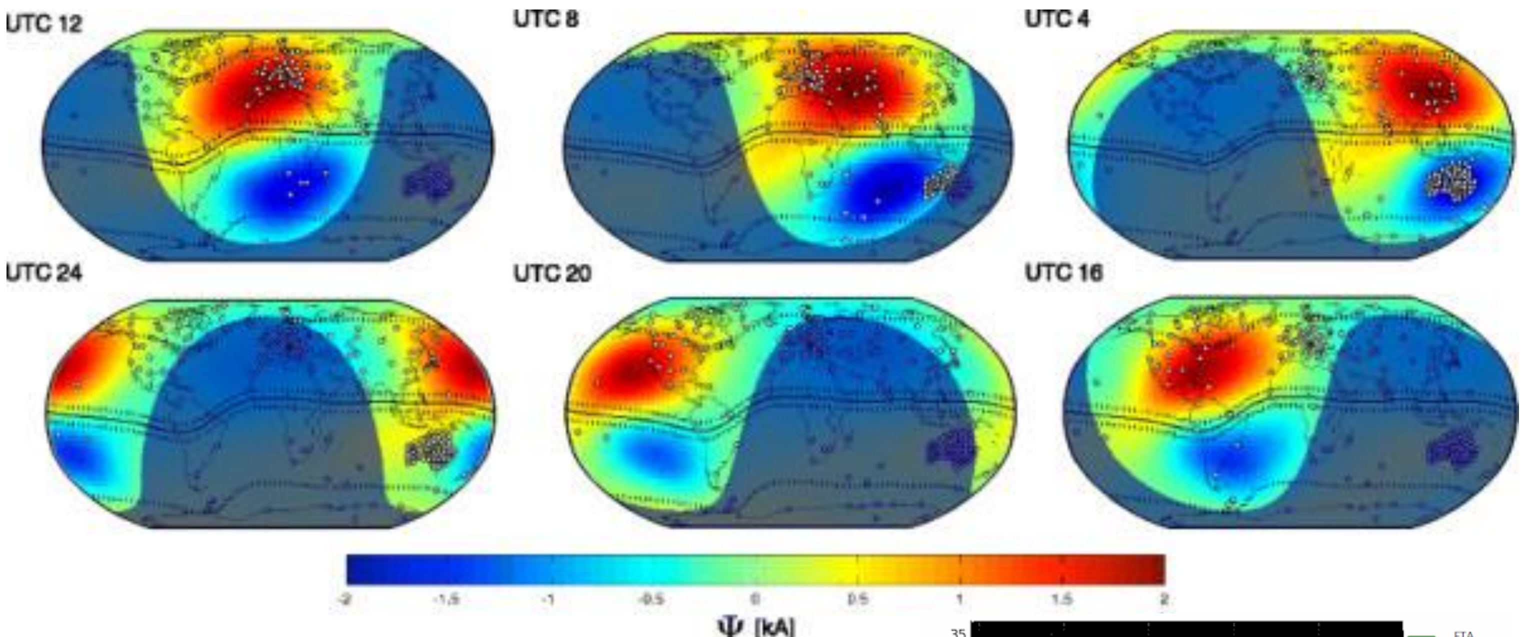
$Y = H \sin(D)$

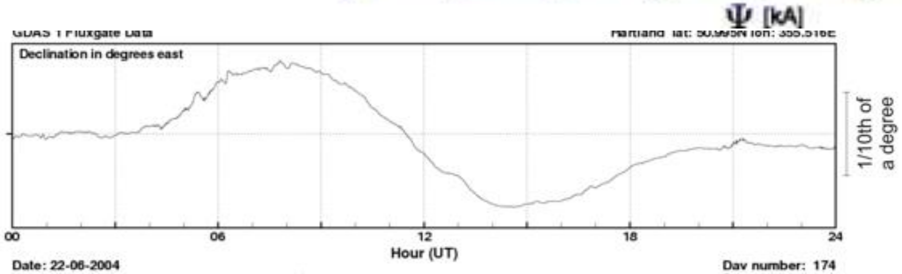
$dY = H \cos(D)\, dD$ For small dD

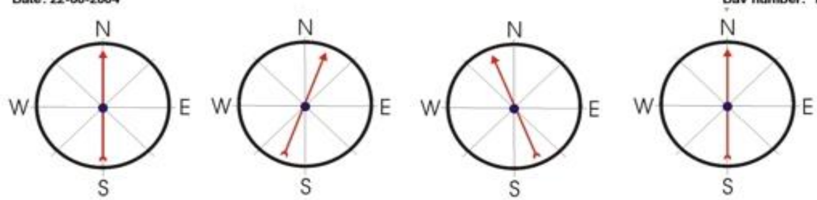
A current system in the ionosphere is created and maintained by solar EUV radiation

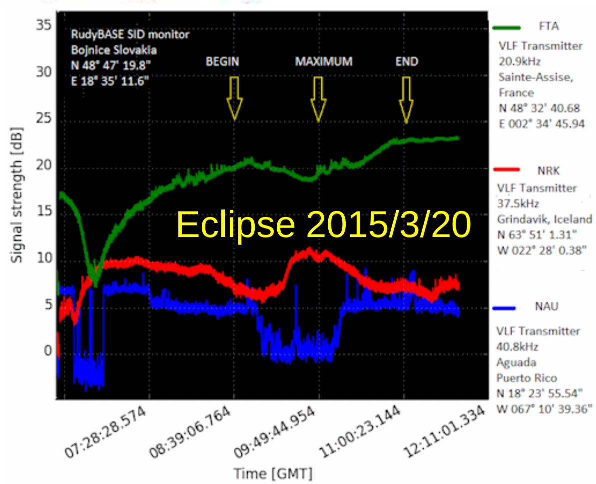
The magnetic effect of this system was what George Graham discovered

The Earth Rotates Under the Current









Electron Density due to EVU

< 102.7 nm

$$O_2 + h\nu \xrightarrow{J} O_2^+ + e^-$$

$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$

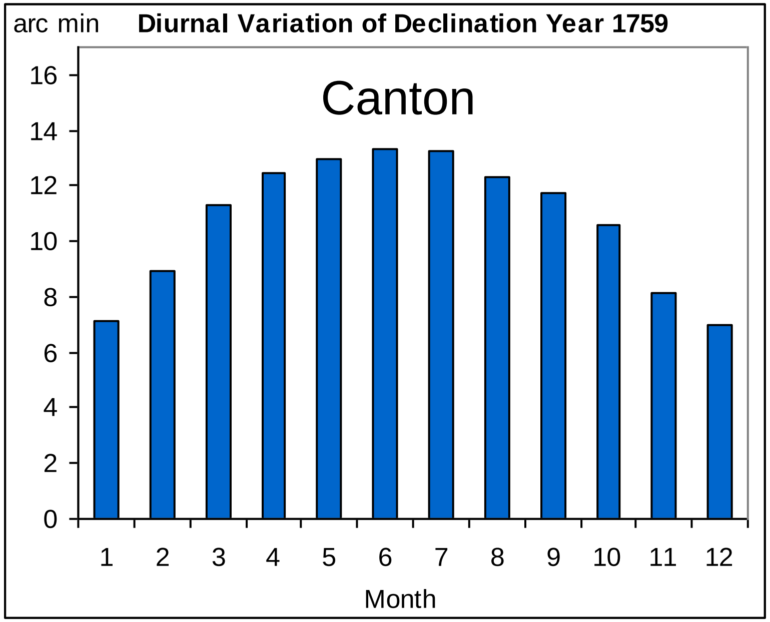
The conductivity at a given height is proportional to the electron number density N_e. In the dynamo region the ionospheric plasma is largely in photochemical equilibrium. The dominant plasma species is $O^+{}_2$, which is produced by photo ionization at a rate J (s^{-1}) and lost through recombination with electrons at a rate α (s^{-1}), producing the Airglow.

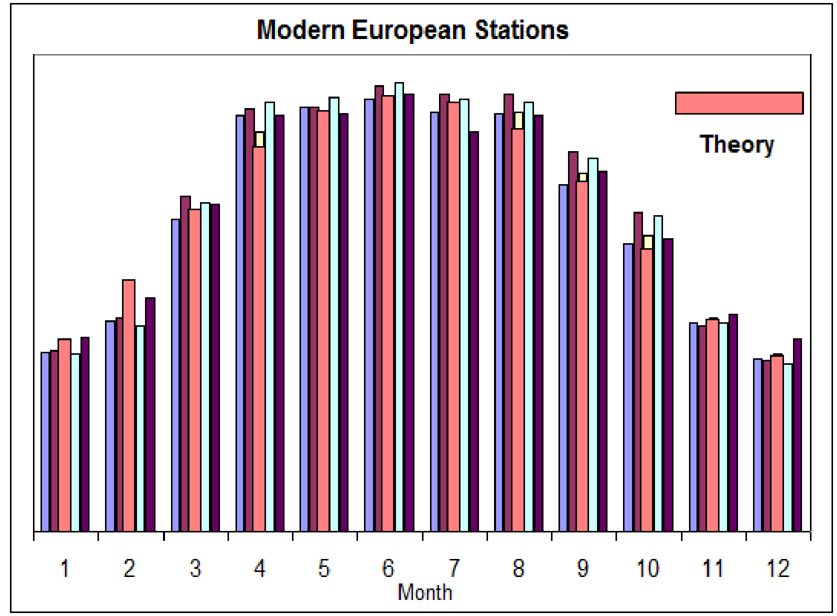
The rate of change of the number of ions N_i, dN_i/dt and in the number of electrons N_e, dN_e/dt are given by $dN_i/dt = J\cos(\chi) - \alpha N_i N_e$ and $dN_e/dt = J\cos(\chi) - \alpha N_e N_i$. Because the process is slow (the Zenith angle χ changes slowly) we have a quasi steady-state, in which there is no net electric charge, so $N_i = N_e = N$. In a steady-state $dN/dt = 0$, so the equations can be written $0 = J\cos(\chi) - \alpha N^2$, and so finally

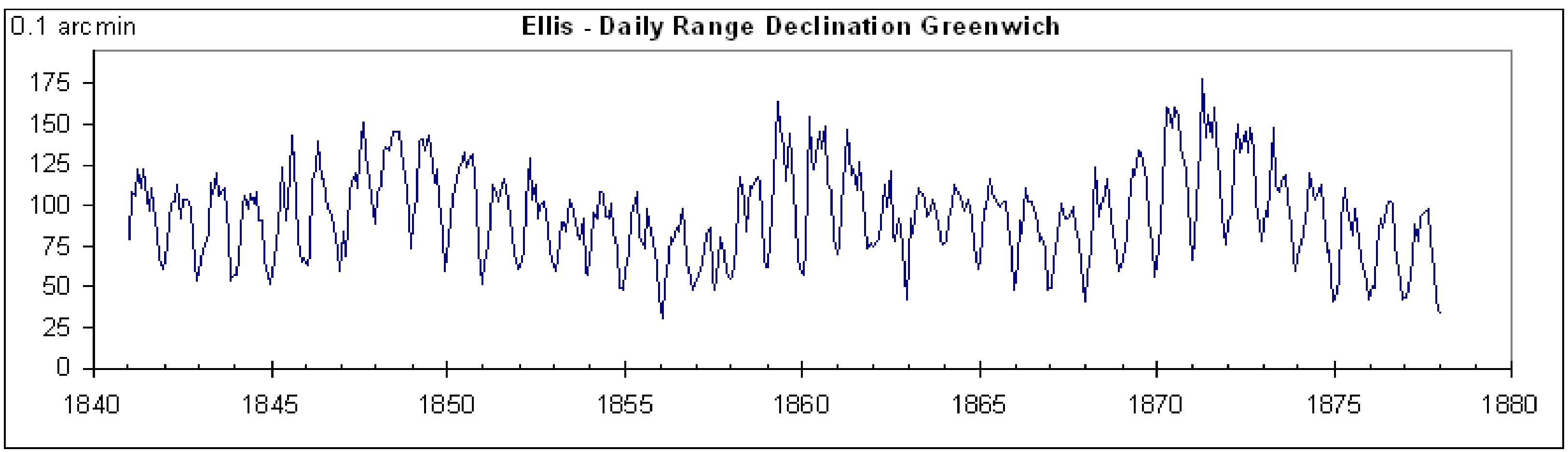
$$N = \sqrt{(J\,\alpha^{-1}\cos(\chi))}$$

Since the conductivity, Σ, depends on the number of electrons N, we expect that Σ scales with the square root $\sqrt{(\boldsymbol{J})}$ of the overhead EUV flux with $\lambda < 102.7$ nm.

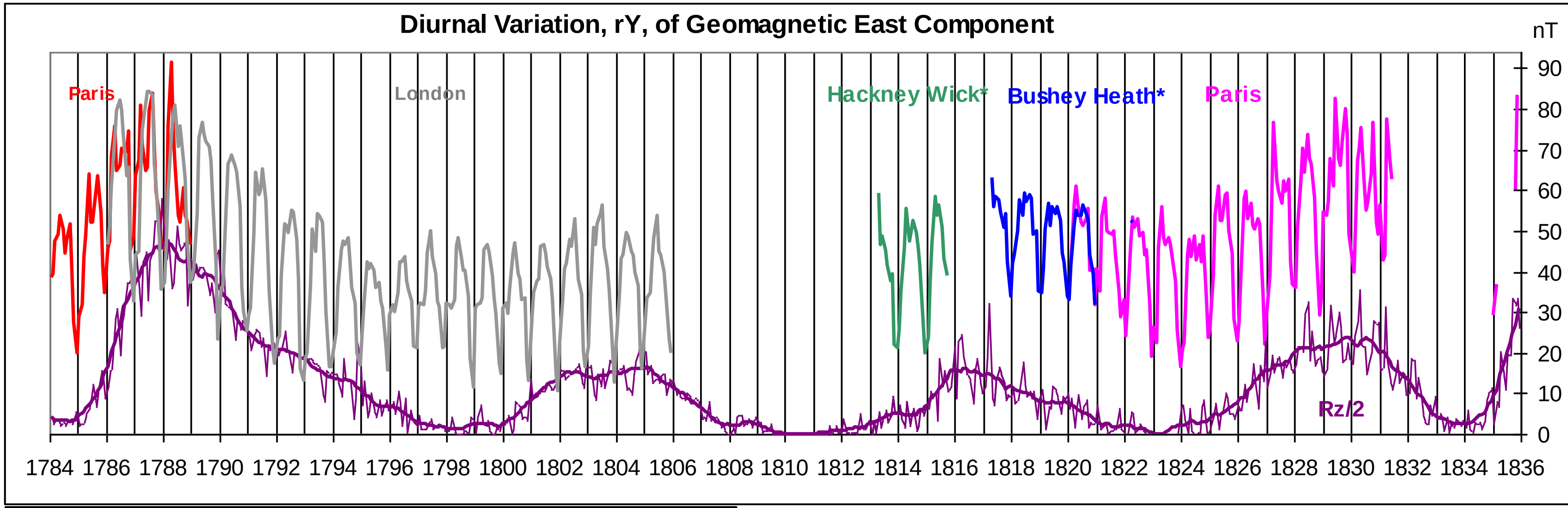
Zenith Angle Dependence Confirmed

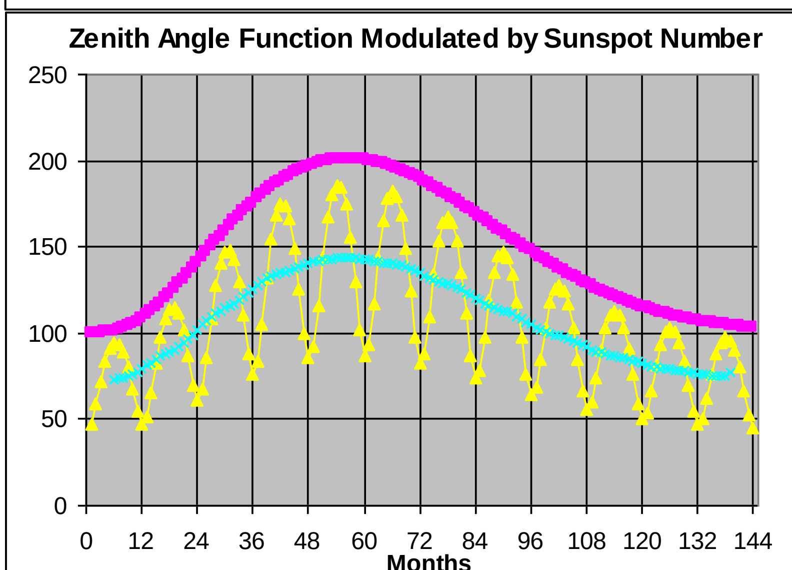


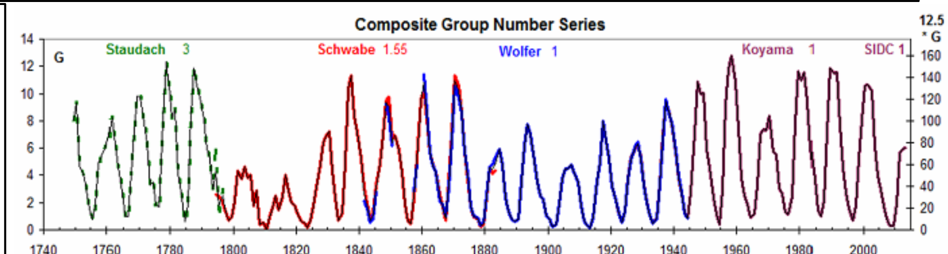


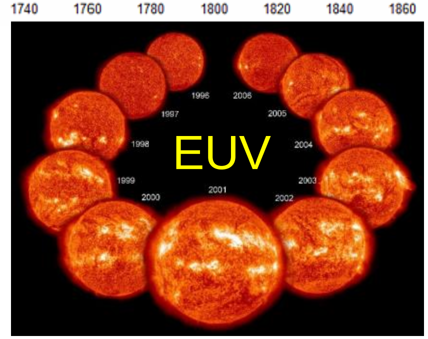


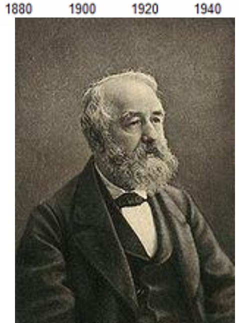
Solar Cycle and Zenith Angle Control





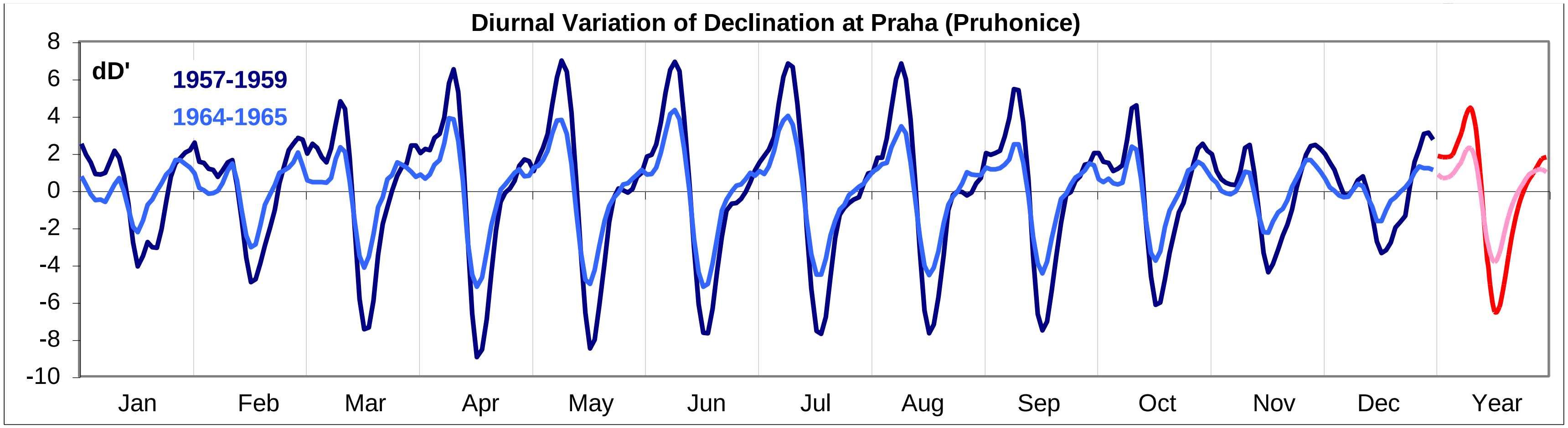


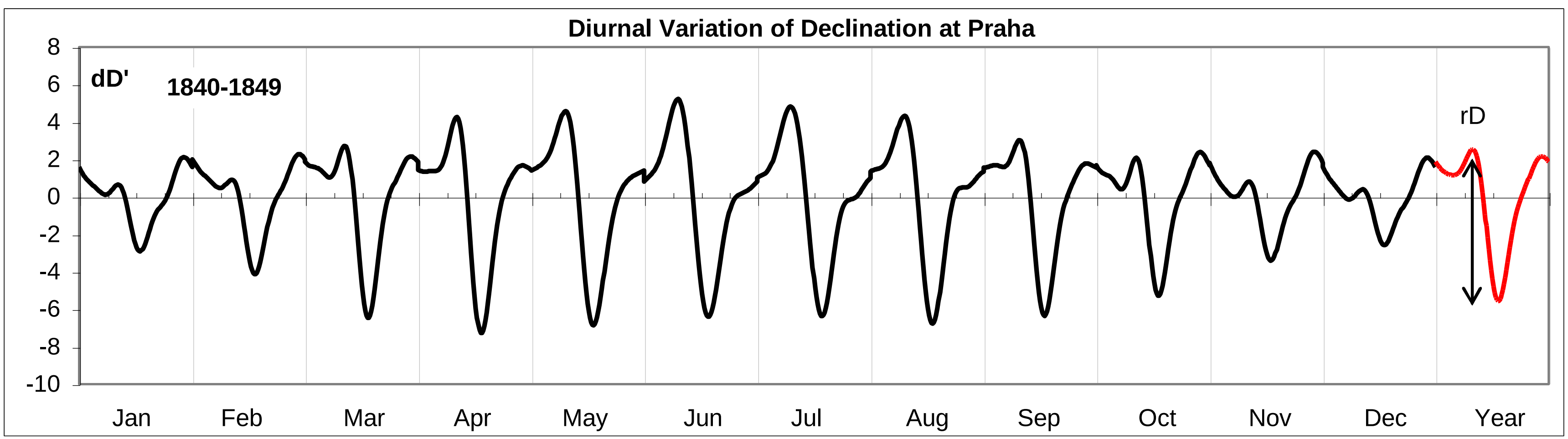




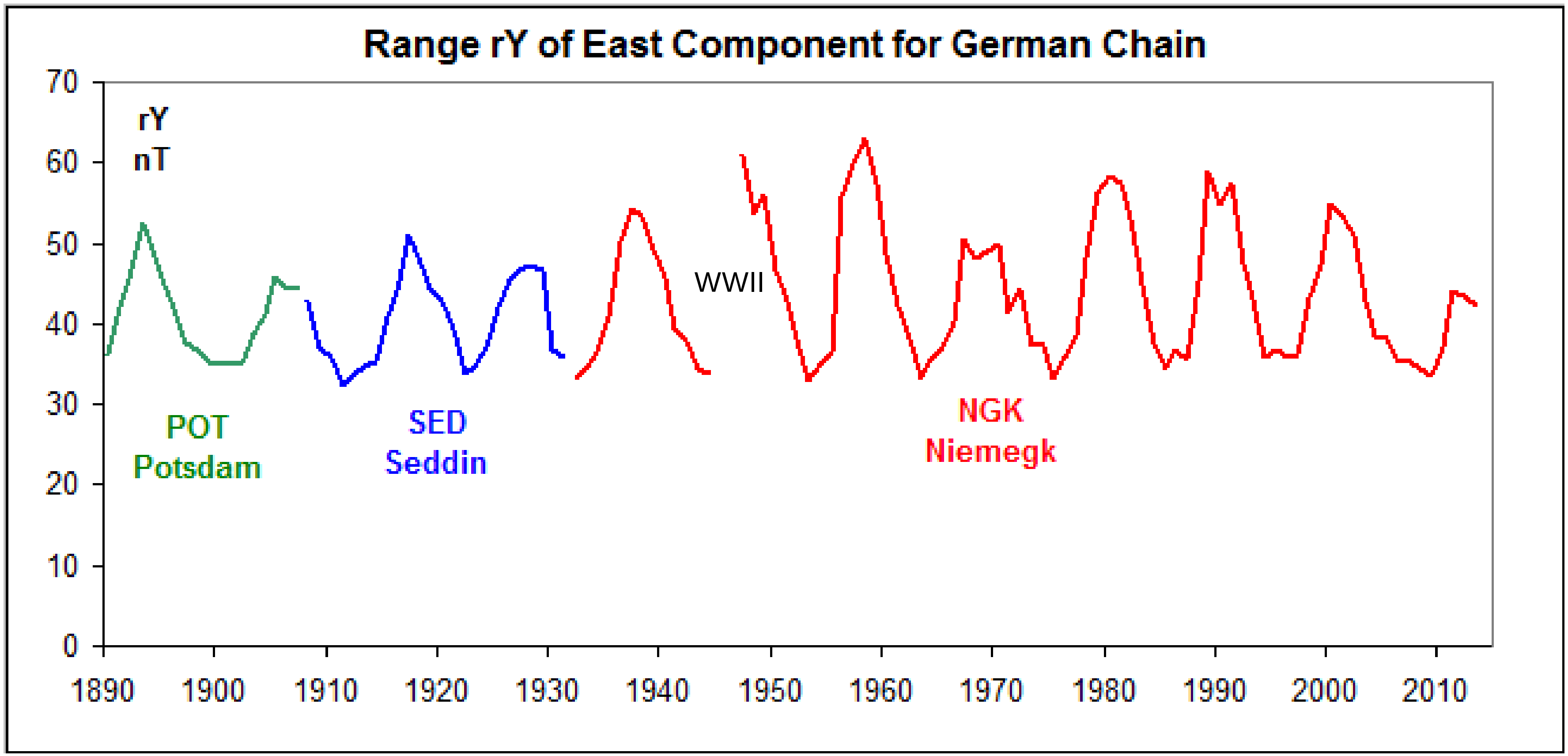
Rudolf Wolf, 1852

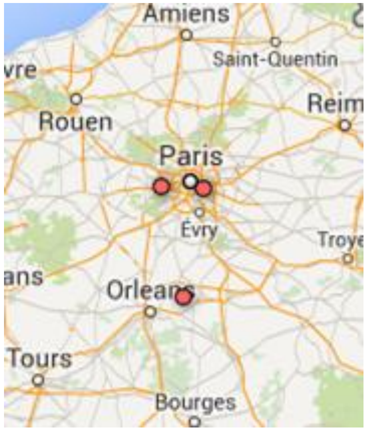
The Diurnal Variation of the Declination for Low, Medium, and High Solar Activity



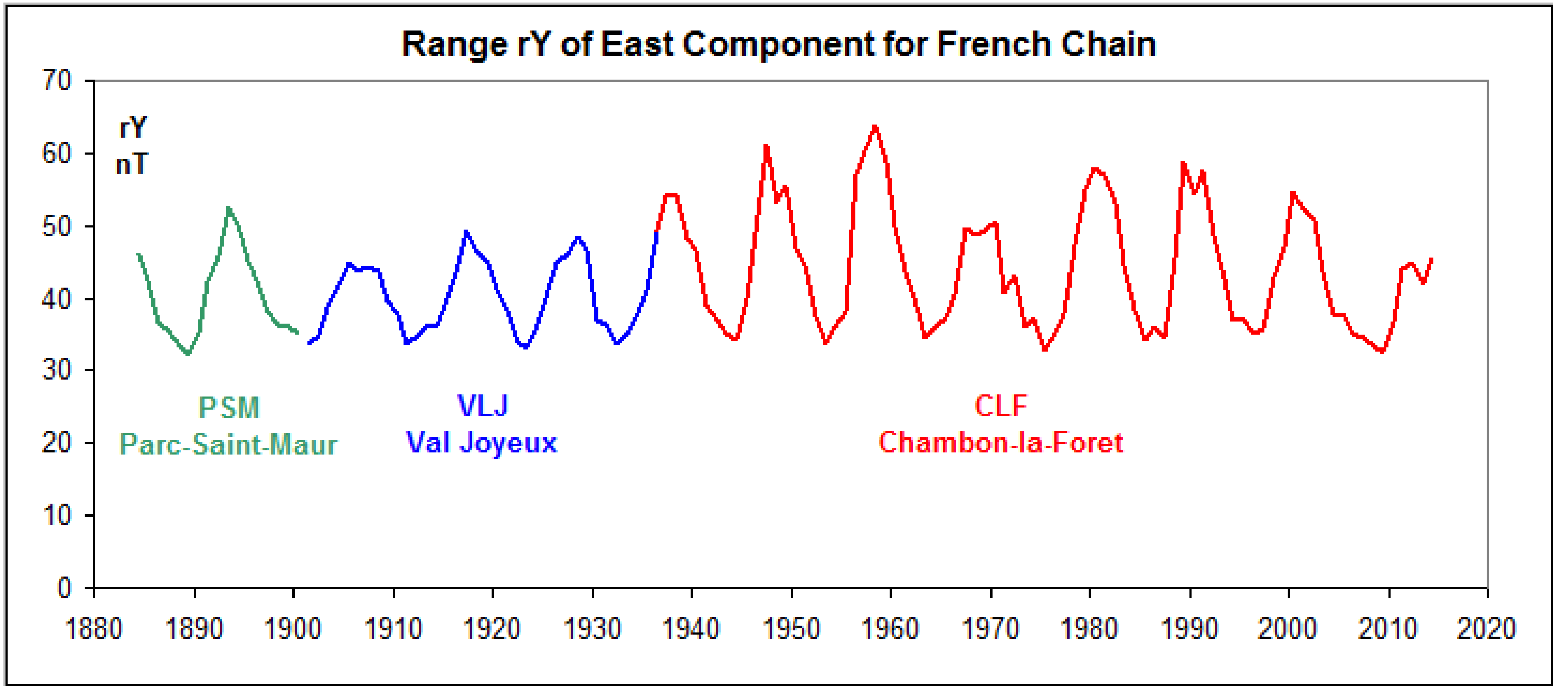


POT-SED-NGK
1890-2013

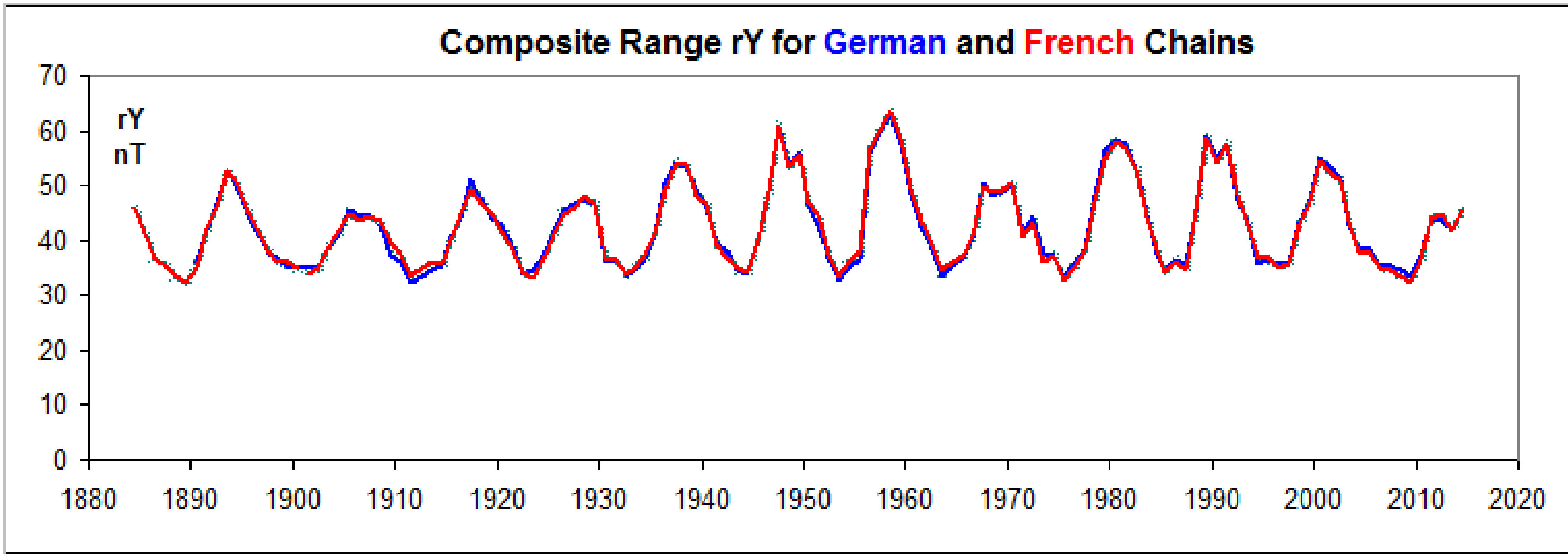




PSM-VLJ-CLF
1884-2014

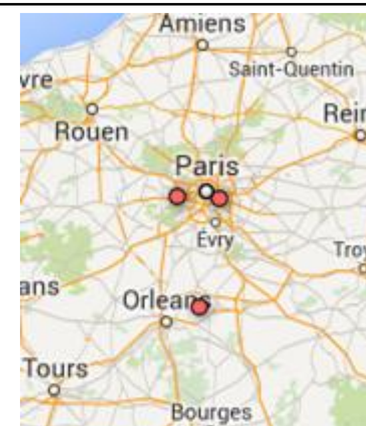


PSM-POT-VLJ-SED-CLF-NGK

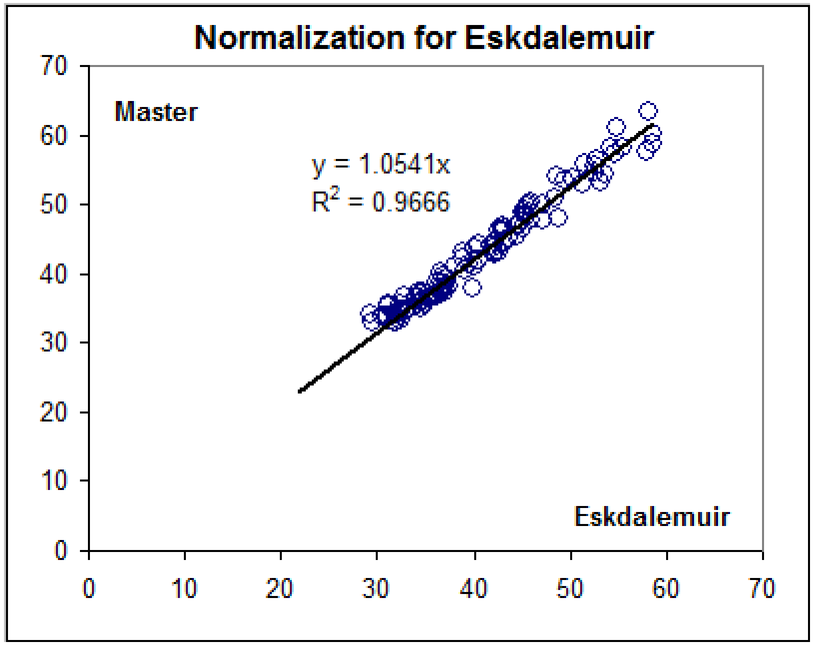


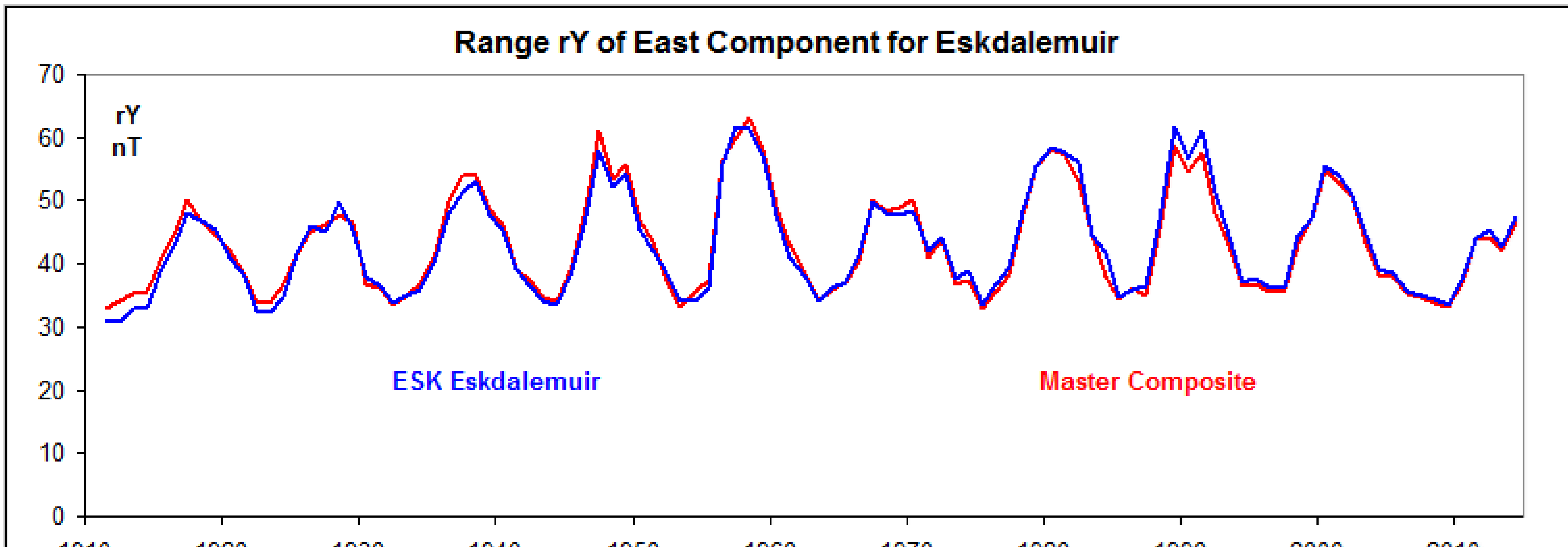
A 'Master' record can now be build by averaging the German and French chains.

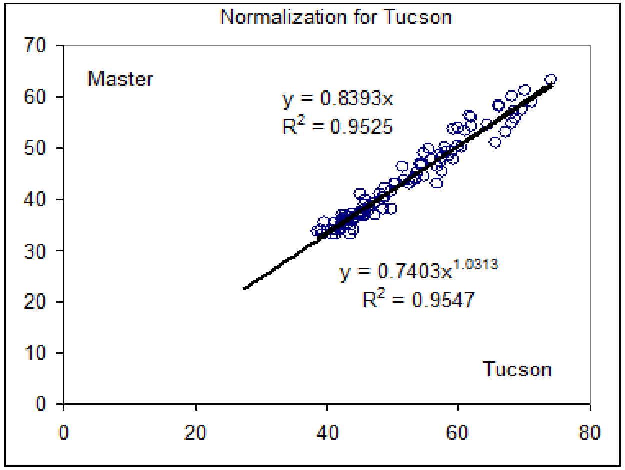
We shall normalize all other stations to this Master record.



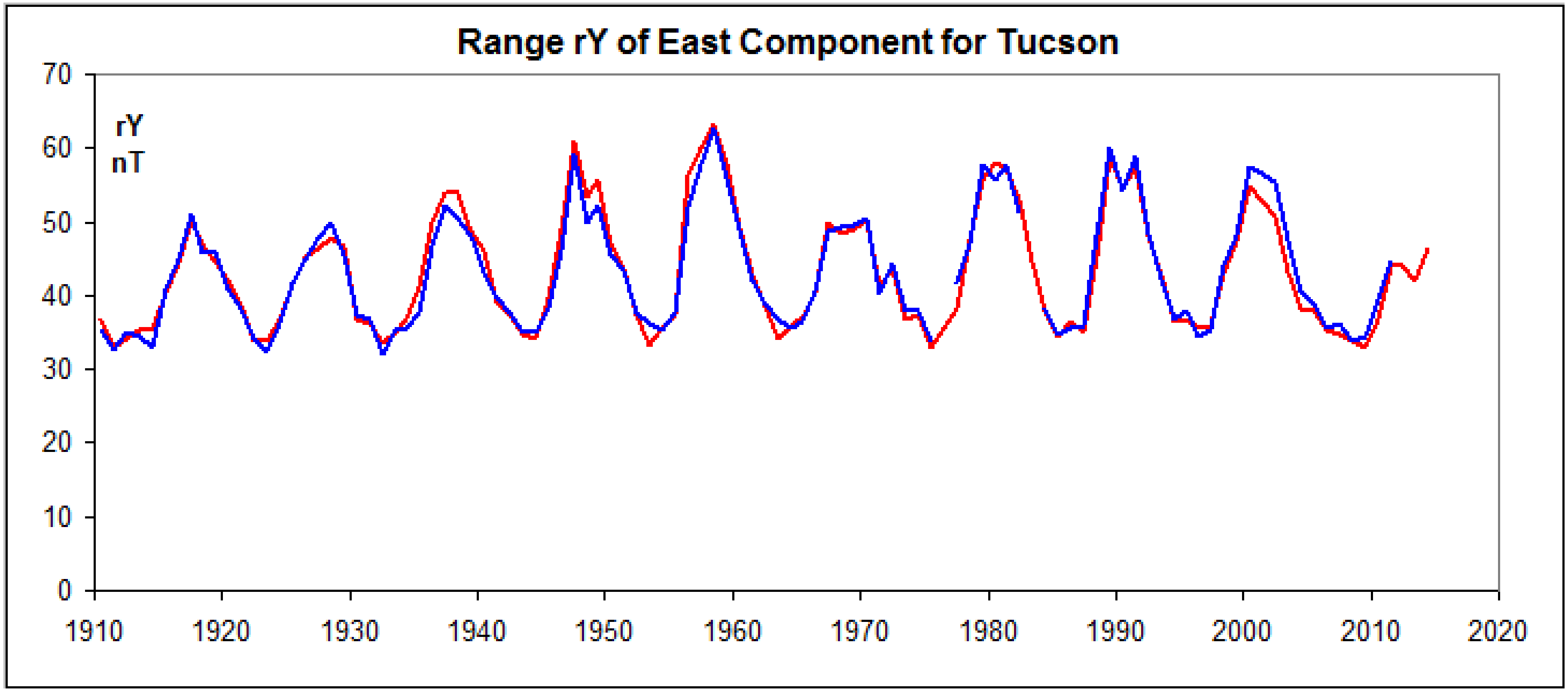
An Example of an Unbroken Series: Eskdalemuir



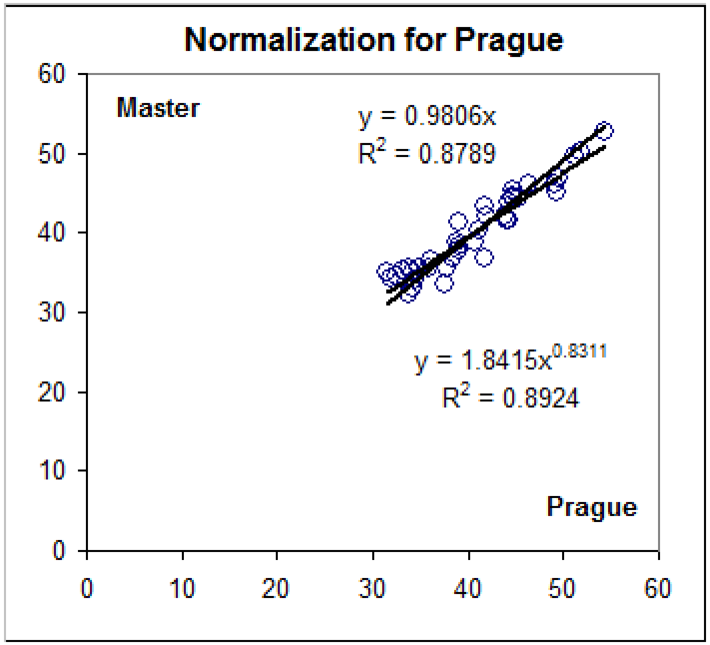




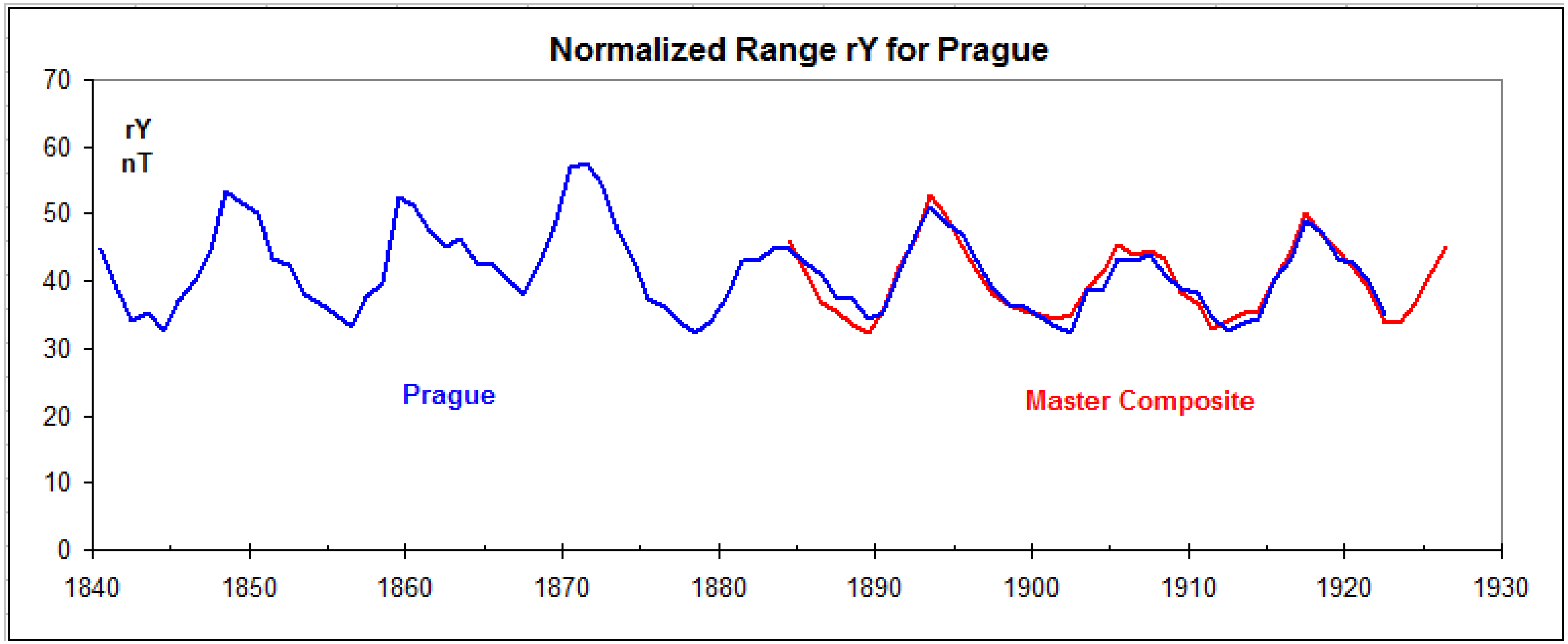
Add Tucson, AZ

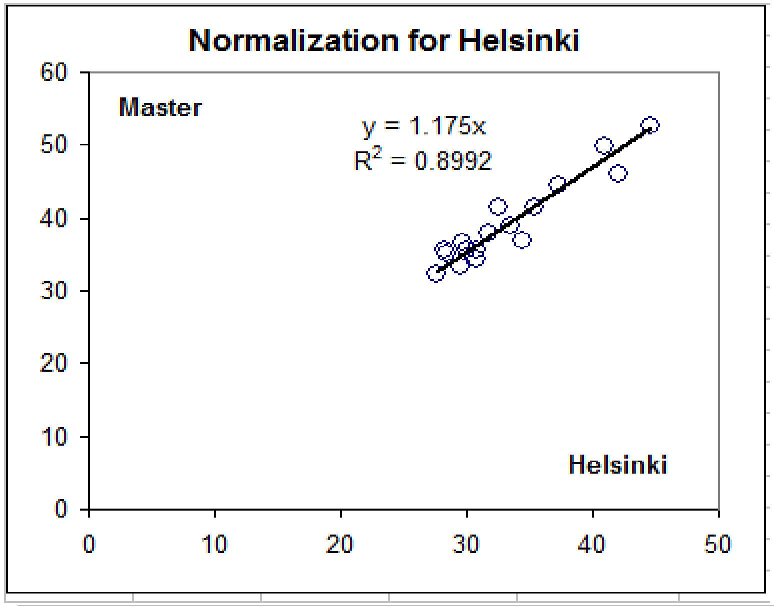


Adding Prague back to 1840

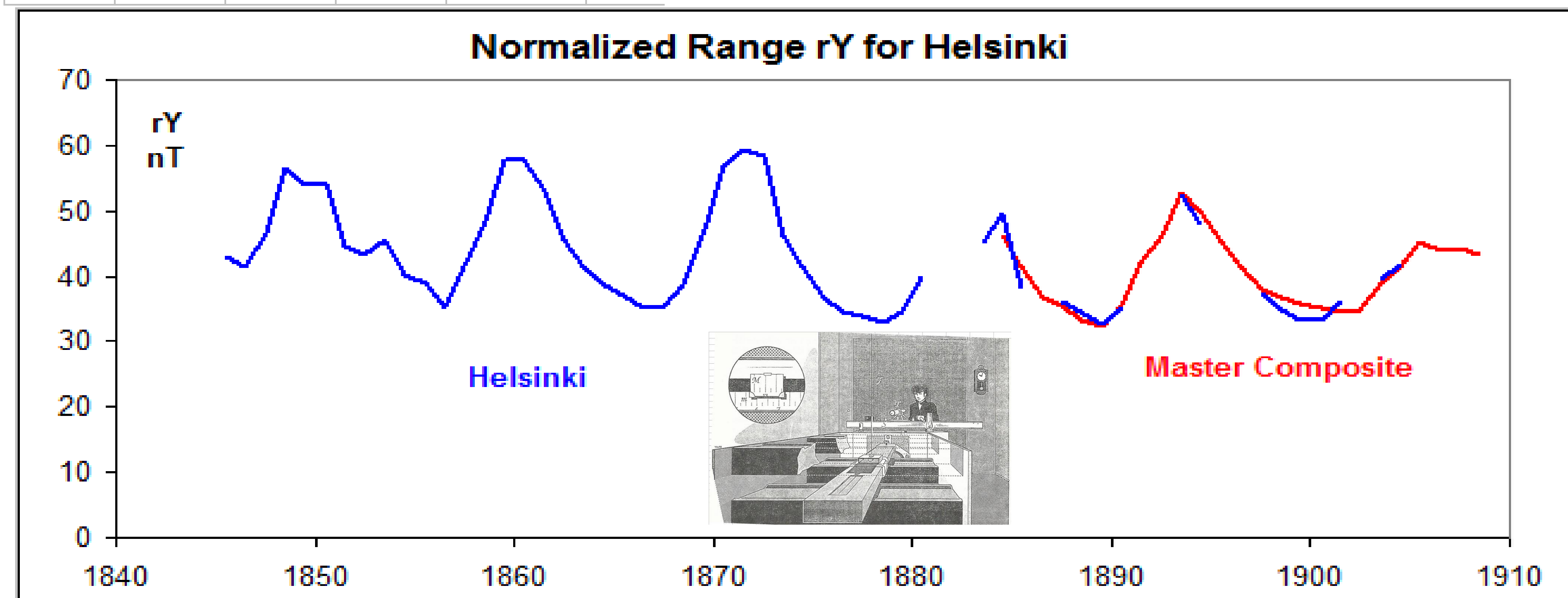


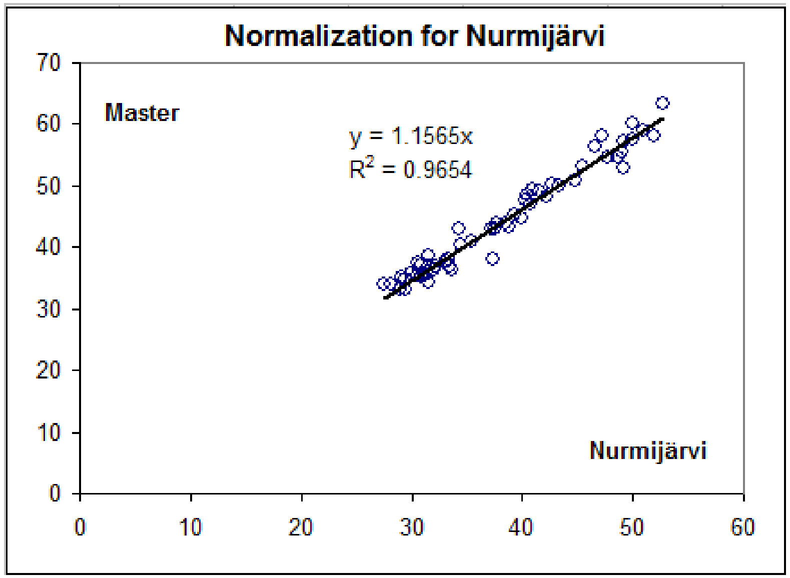
If the regression against the Master record is not quite linear, a power law is used.



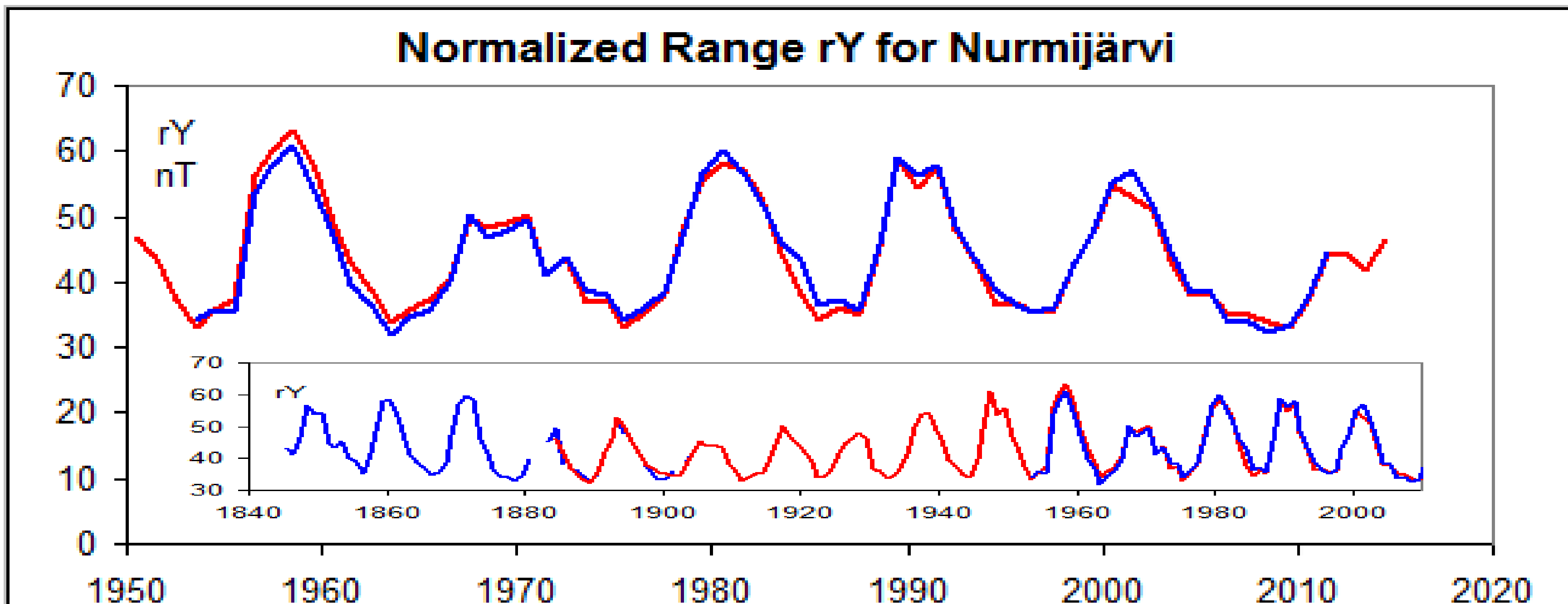


Adding Helsinki back to 1845





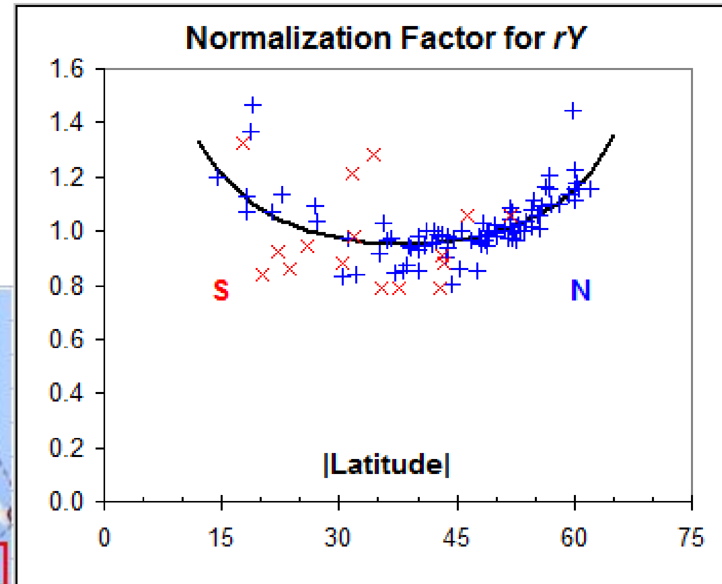
Adding its replacement observatory Nurmijärvi

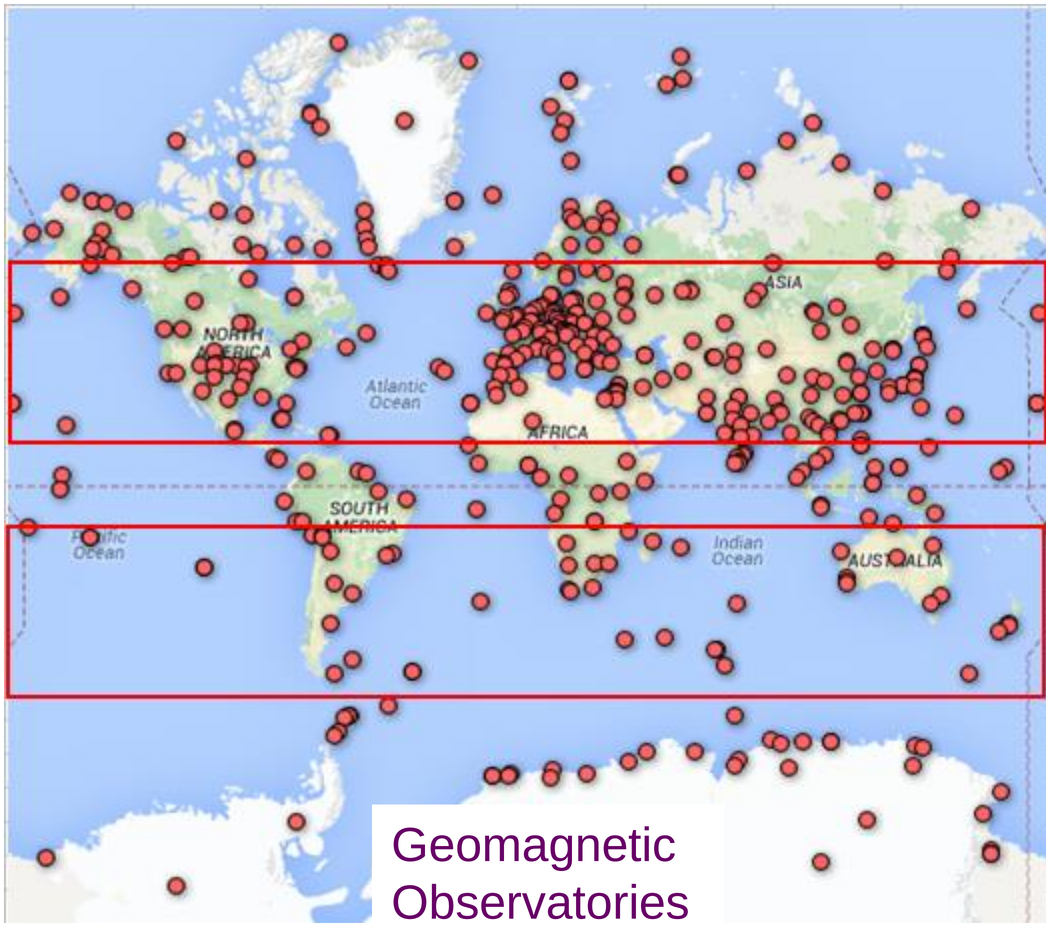


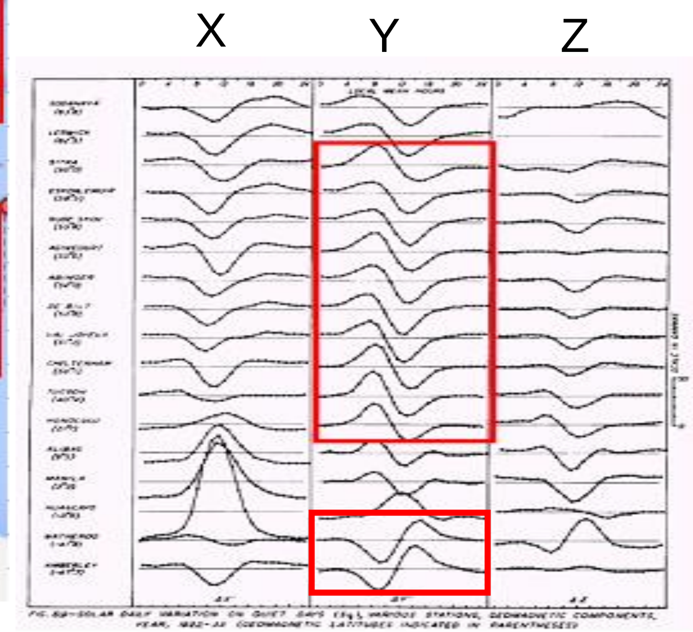
And So On: For 107 Geomagnetic Observatories with Good Data

POT	COI	WIK	BSL	DBN	VAL
SED	WNG	AAA	TOR	WIT	VIC
NGK	TOK	ARS	MON	FUR	YAK
PSM	HRB	ASP	AML	WLH	SPE
VLJ	TOO	BDV	AQU	EKT	MIL
CLF	WAT	BEL	BTV	BAL	BER
KAK	SIT	BJI	PET	OSL	TFS
ESK	SSH	BOU	ROM	CLA	MBO
HLS	PIL	BOX	EYR	ABG	CBI
NUR	LOV	SFS	FRN	WIE	LRM
CLH	RSV	CDP	GNA	GRW	NVS
FRD	BFE	CNB	HLP	MNH	PAG
HON	HER	CTA	EBR	KLT	PPT
TUC	SVD	HBK	MIZ	GEN	PST
VQS	AGN	ISK	GCK	MNK	THY
SJG	OTT	LNN	IRT	KNZ	STJ
ABN	HBT	TAM	JAI	DOU	CZT
HAD	PRA	MMB	LER	LVV	

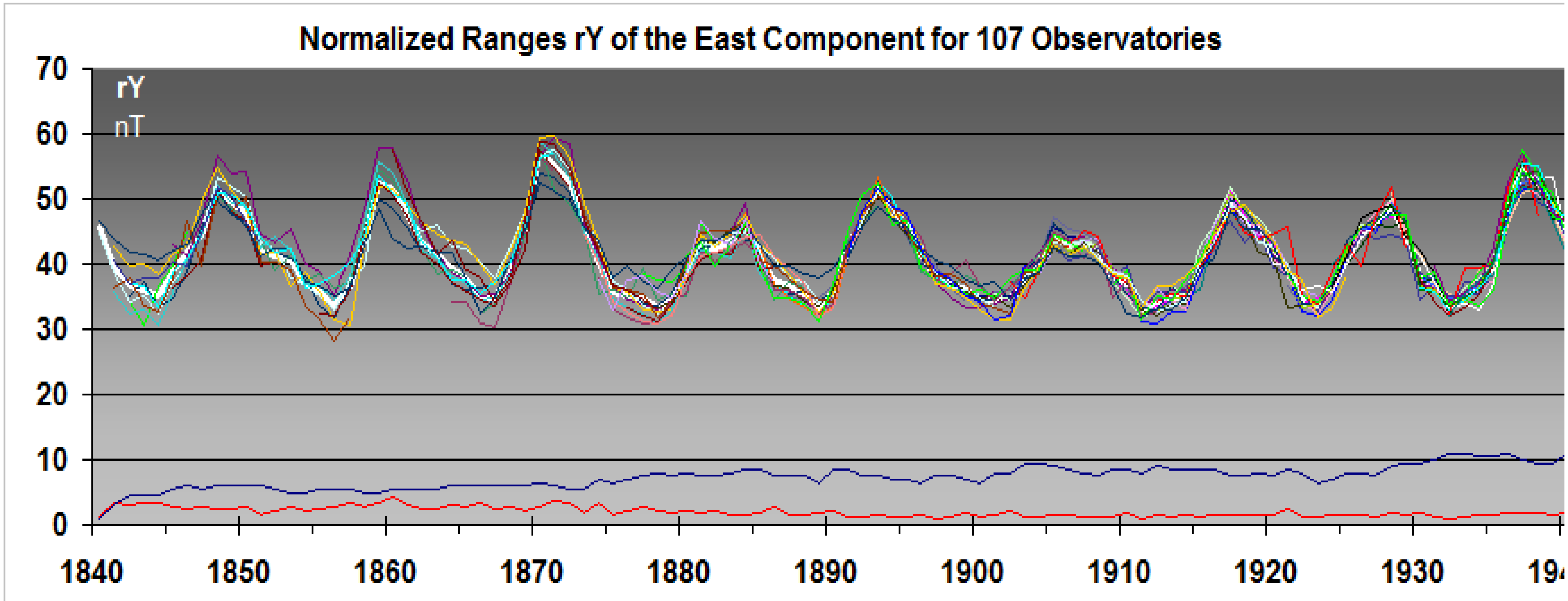
The Magnetic Signal at Midlatitudes

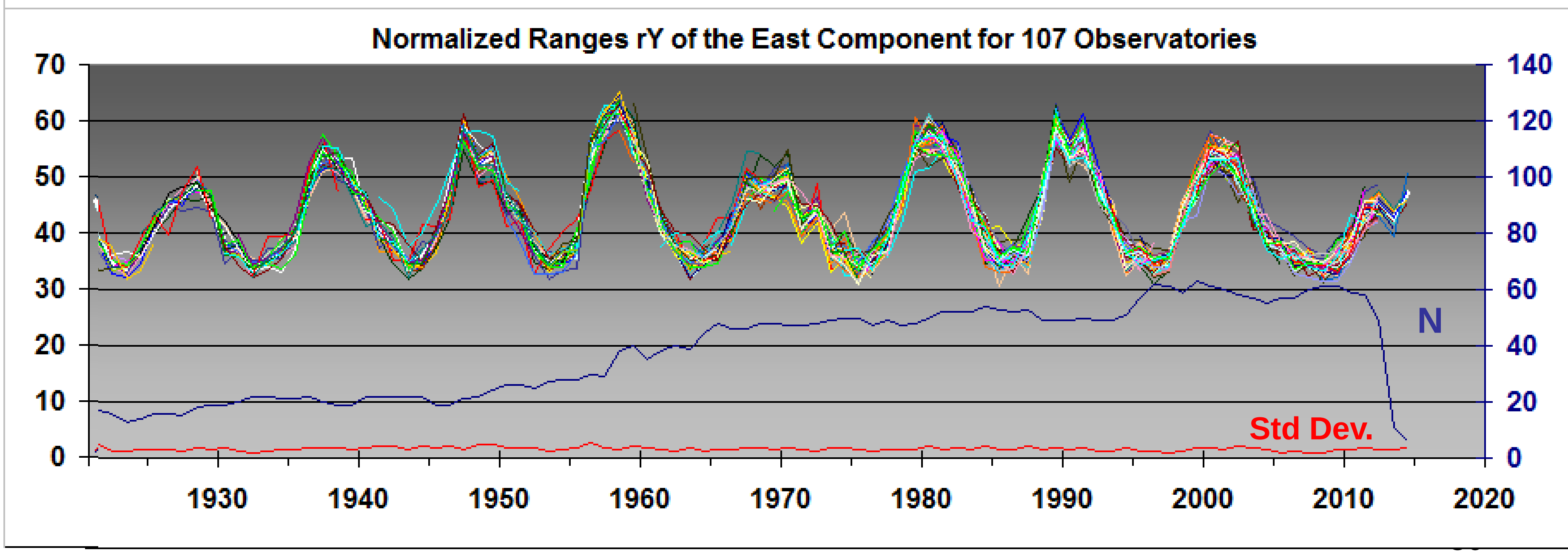




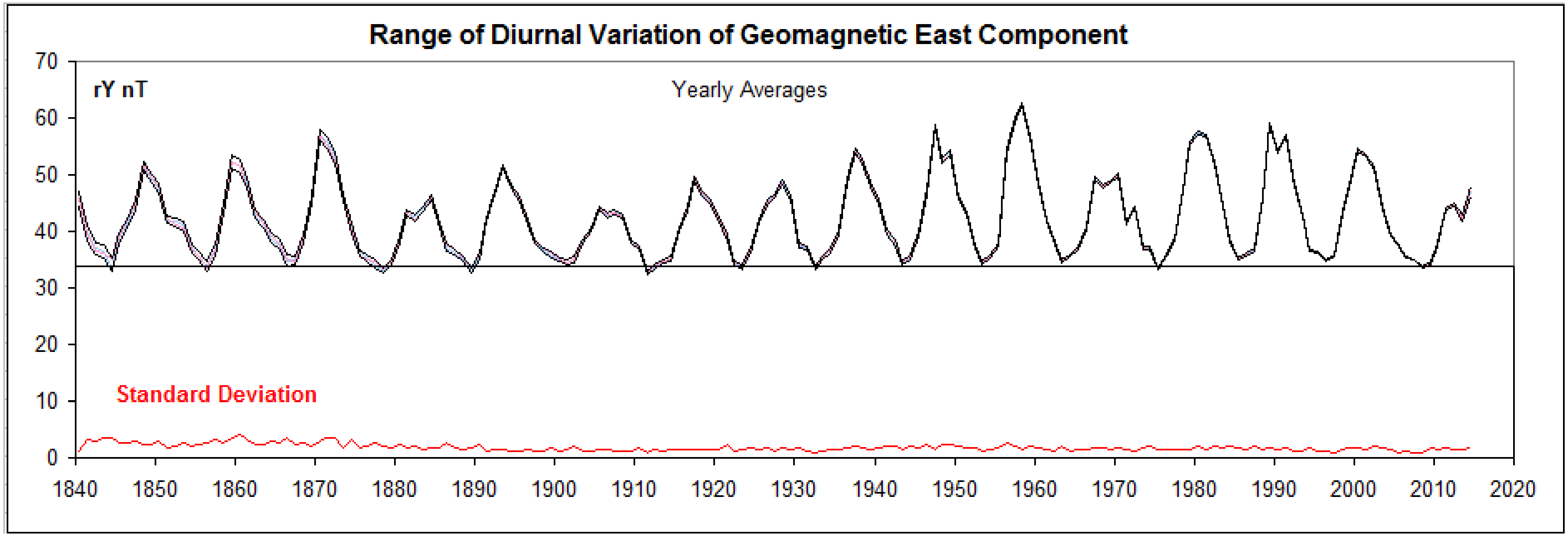


The effect in the Y-component is rather uniform for latitudes between 20º and 60º


Normalized Ranges rY of the East Component for 107 Observatories
rY
nT
70
60
50
40
30
20
10
0
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
194

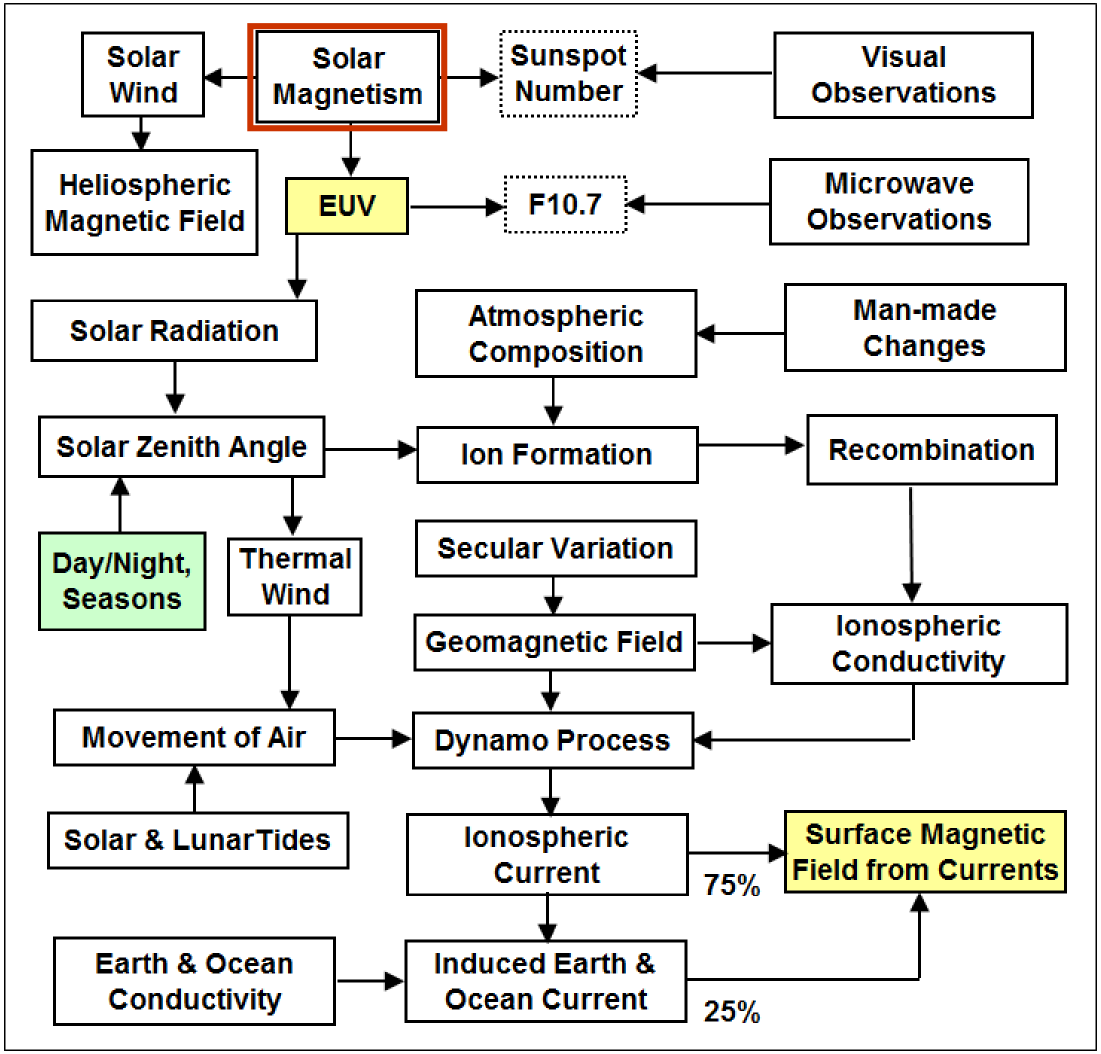

Normalized Ranges rY of the East Component for 107 Observatories
70
60
50
40
30
20
10
0
140
120
100
80
60
40
20
0
N
Std Dev.
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

Composite *rY* Series 1840-2014



From the Standard Deviation and the Number of Station in each Year we can compute the Standard Error of the Mean and plot the ±1-sigma envelope

The Effect of Solar EUV

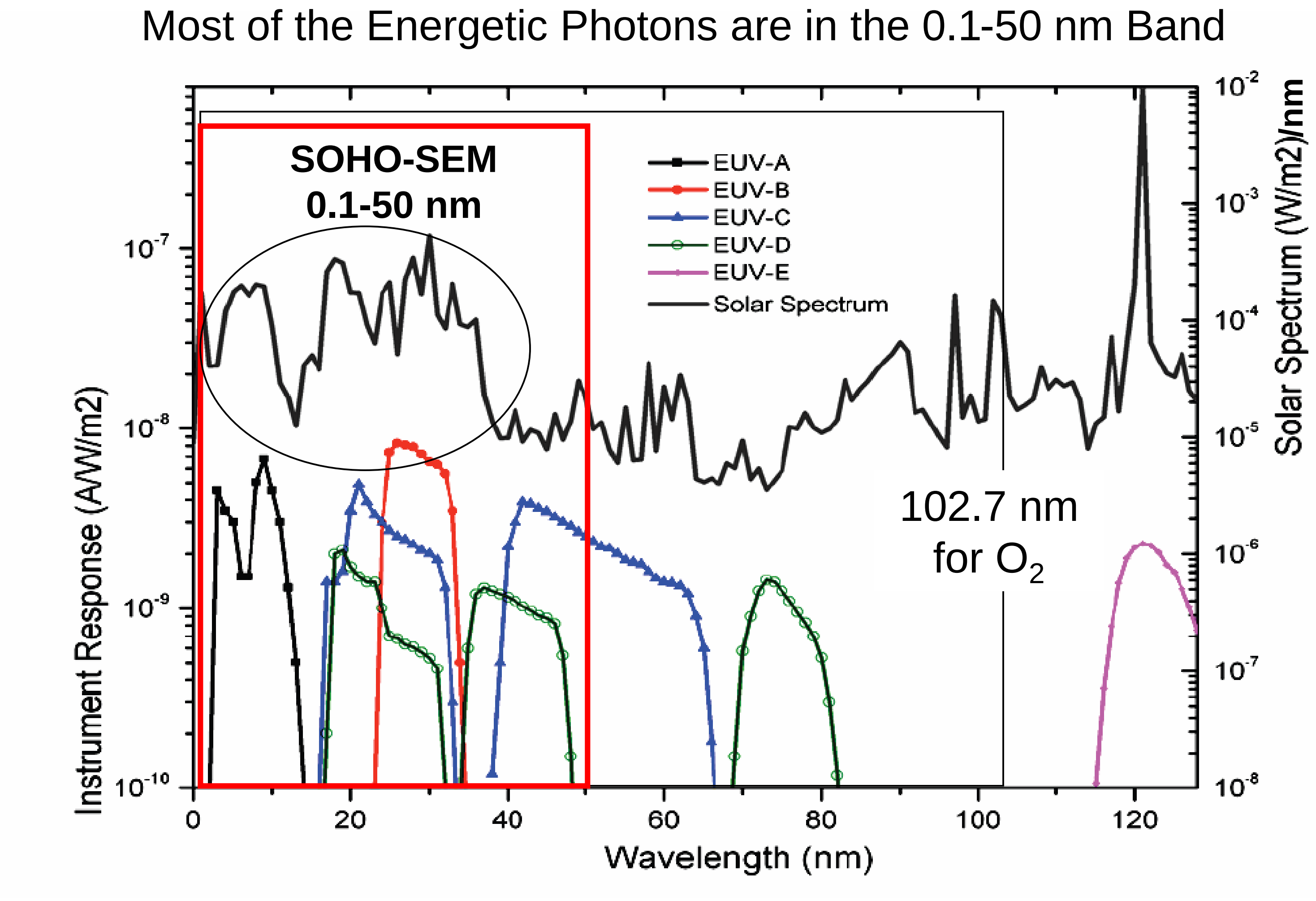


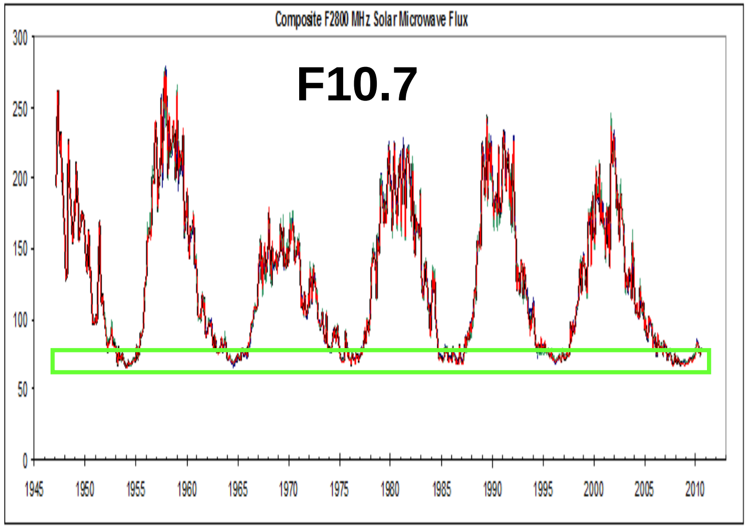
The EUV causes an observable variation of the geomagnetic field at the surface through a complex chain of physical connections.

The physics of each link in the chain is well-understood in quantitative detail and can be successfully modeled.

We'll use this chain in reverse to deduce the EUV flux from the geomagnetic variation.

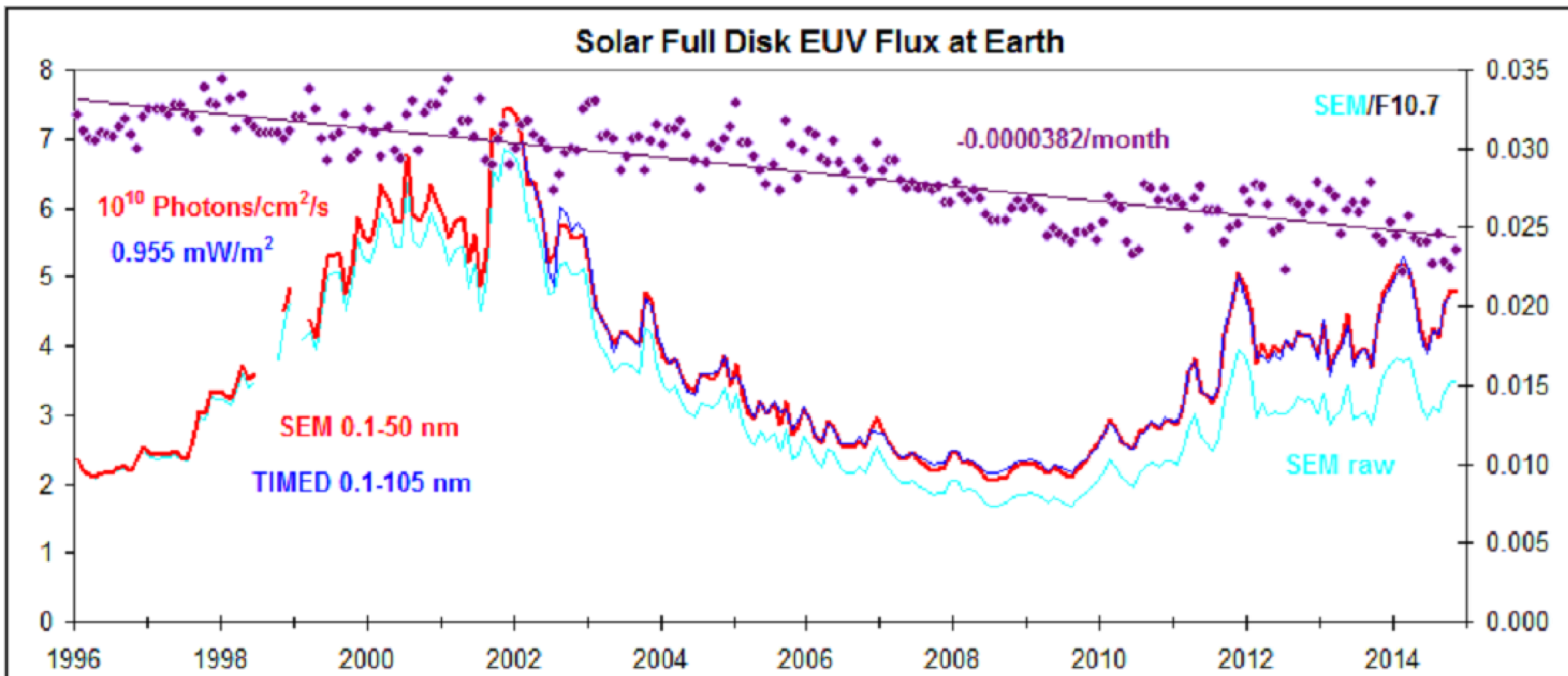
EUV Bands and Solar Spectrum





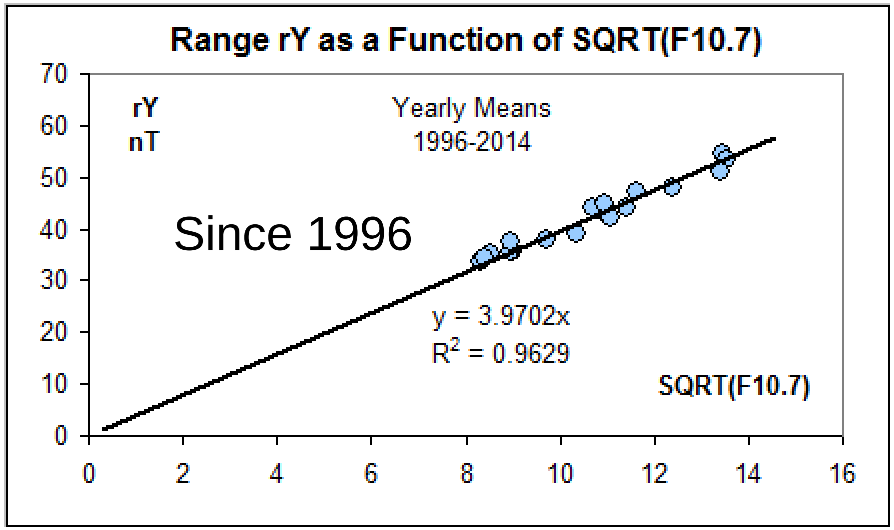
EUV and its proxy: F10.7 Microwave Flux

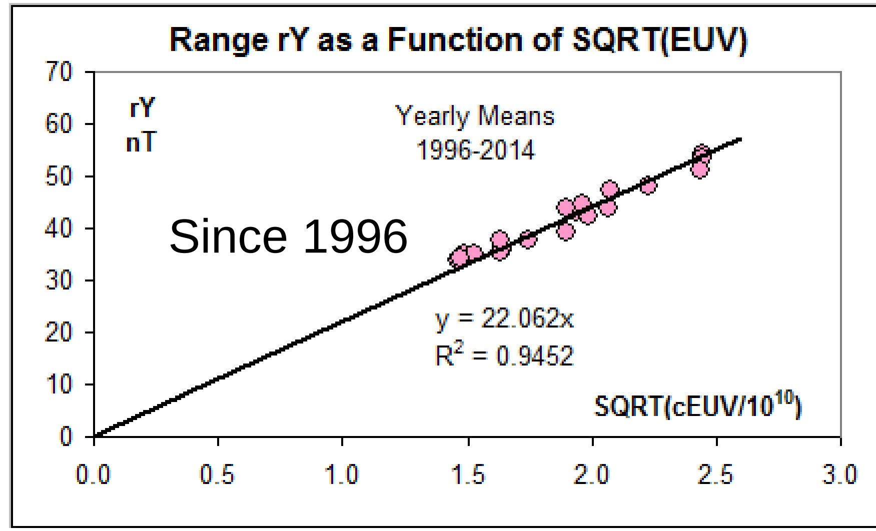
Space is a harsh environment:
Sensor Degradation

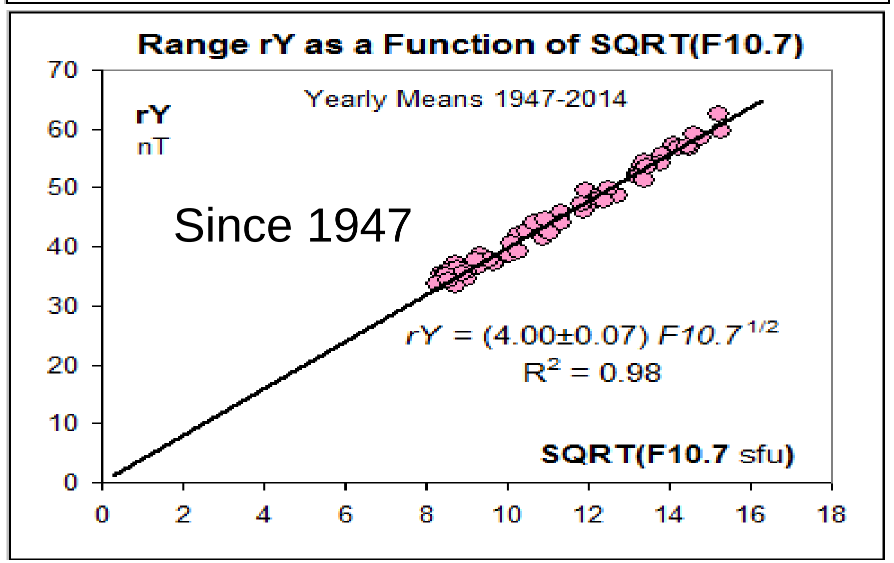


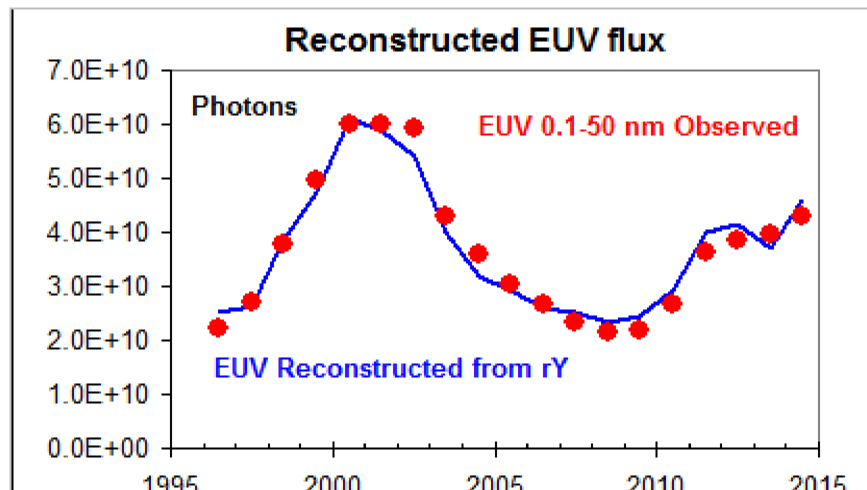
rY and F10.7$^{1/2}$ and EUV$^{1/2}$

√(*J*)

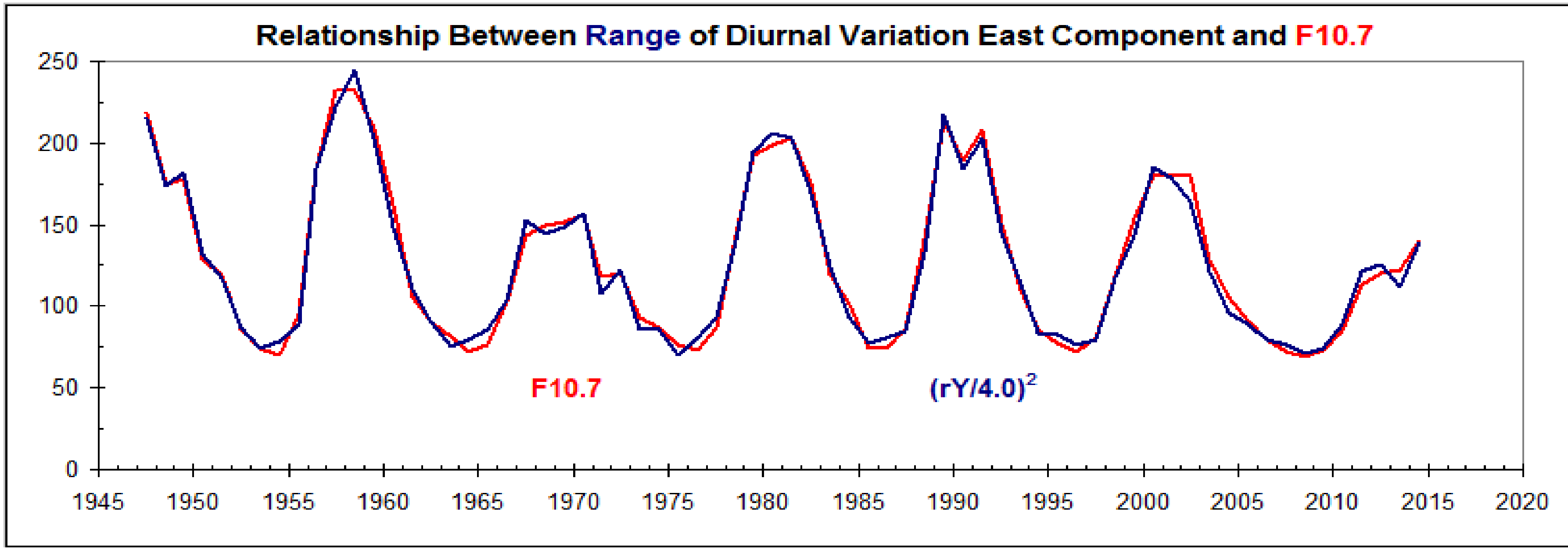


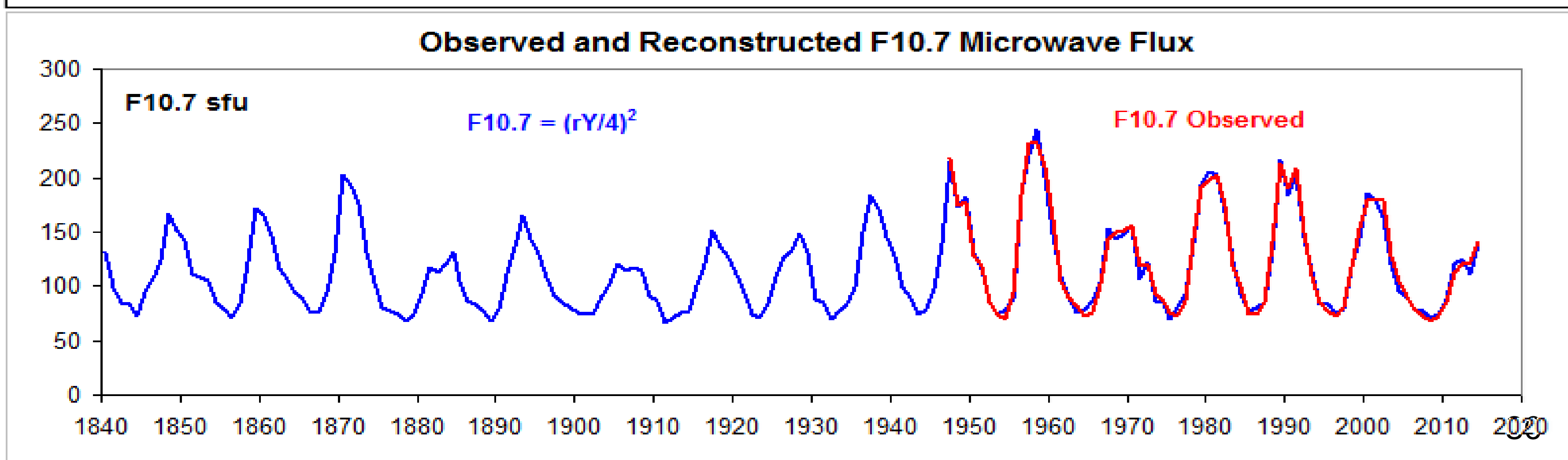




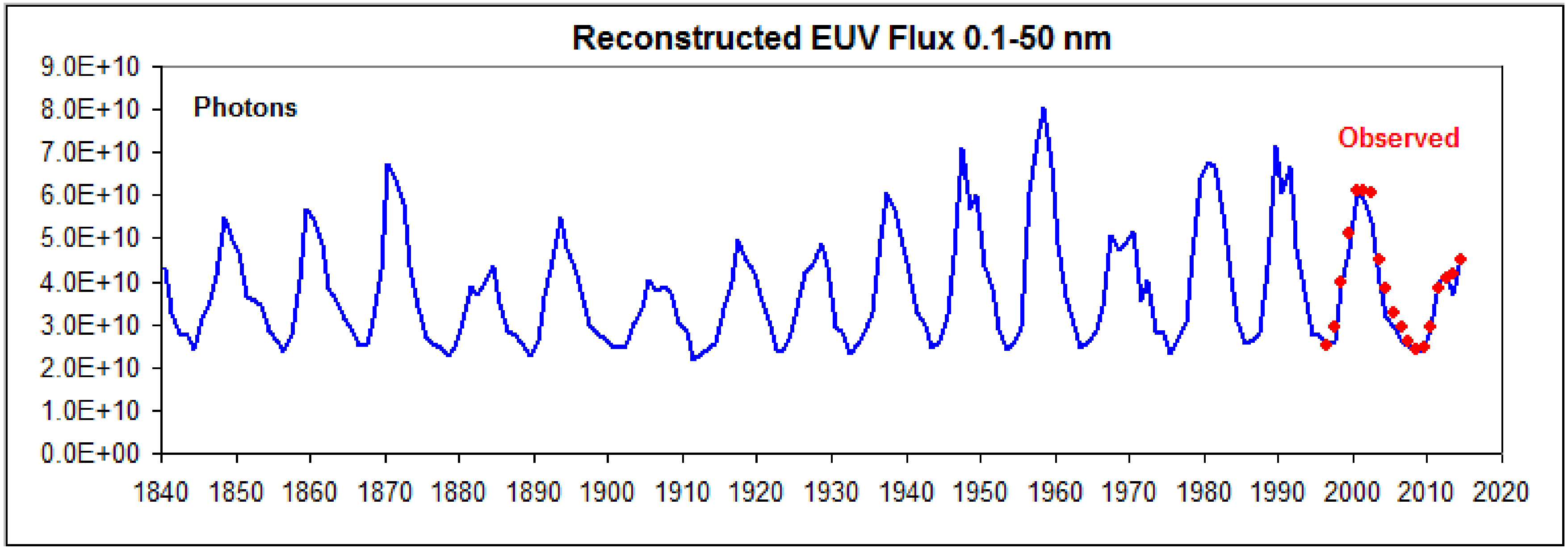


Reconstructed F10.7 [an EUV Proxy]



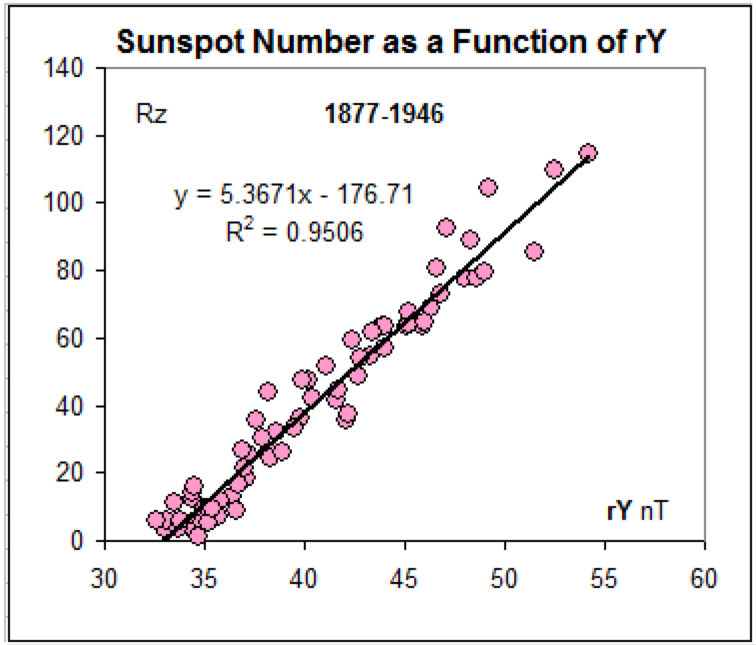


Reconstructed EUV Flux 1840-2014



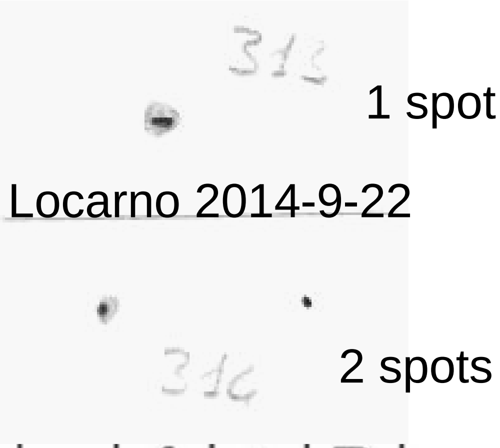
This is, I believe, an accurate depiction of true solar activity since 1840

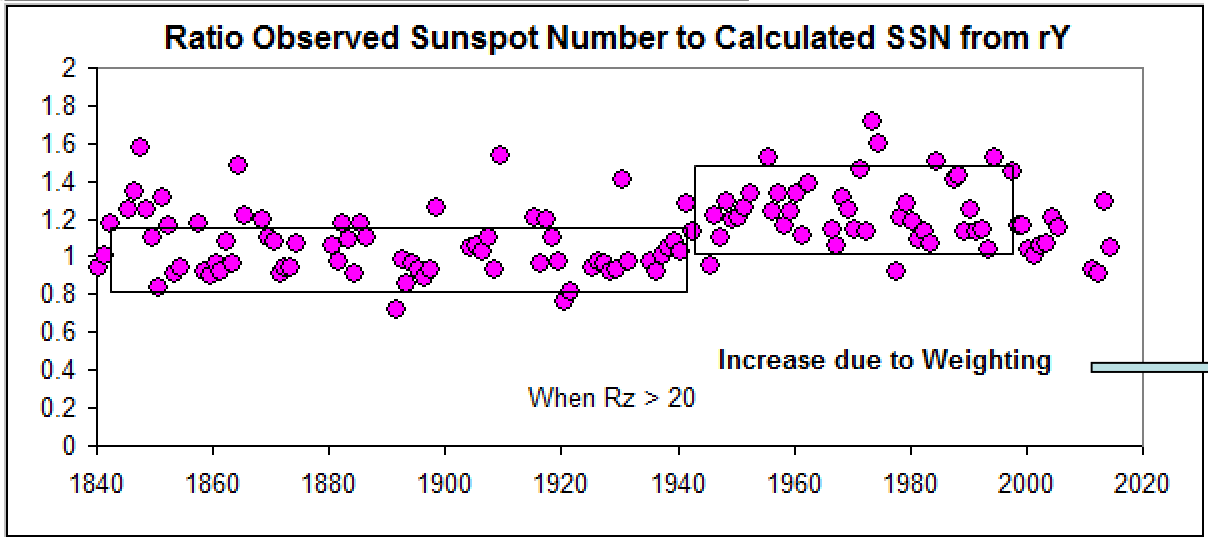
We can compare that with the Zurich Sunspot Number



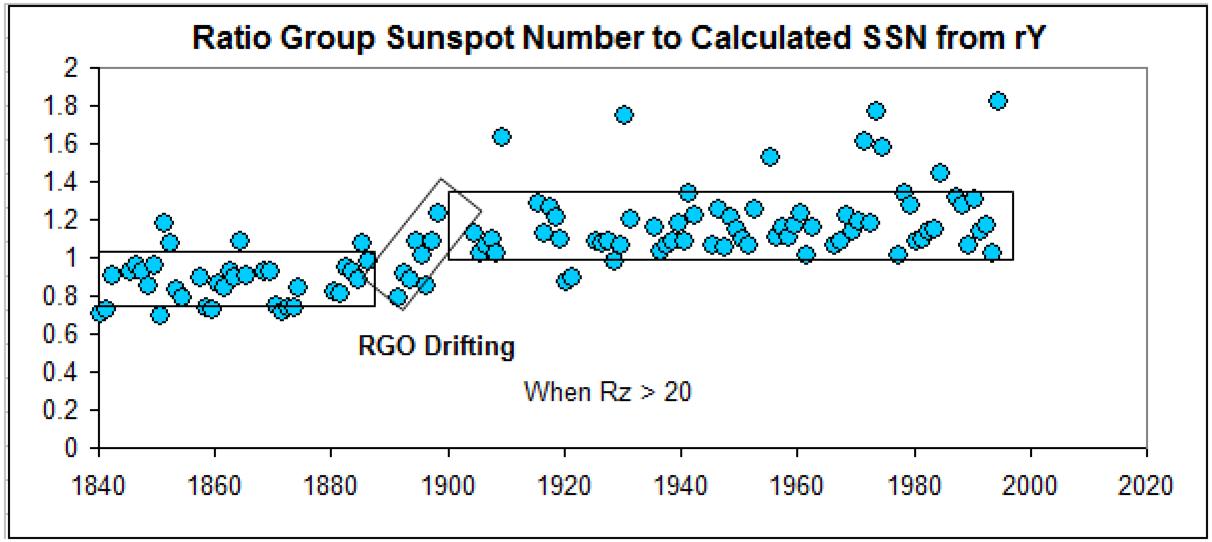
	ratio
1840-1876	1.052
1877-1946	1.000
1947-1999	1.210

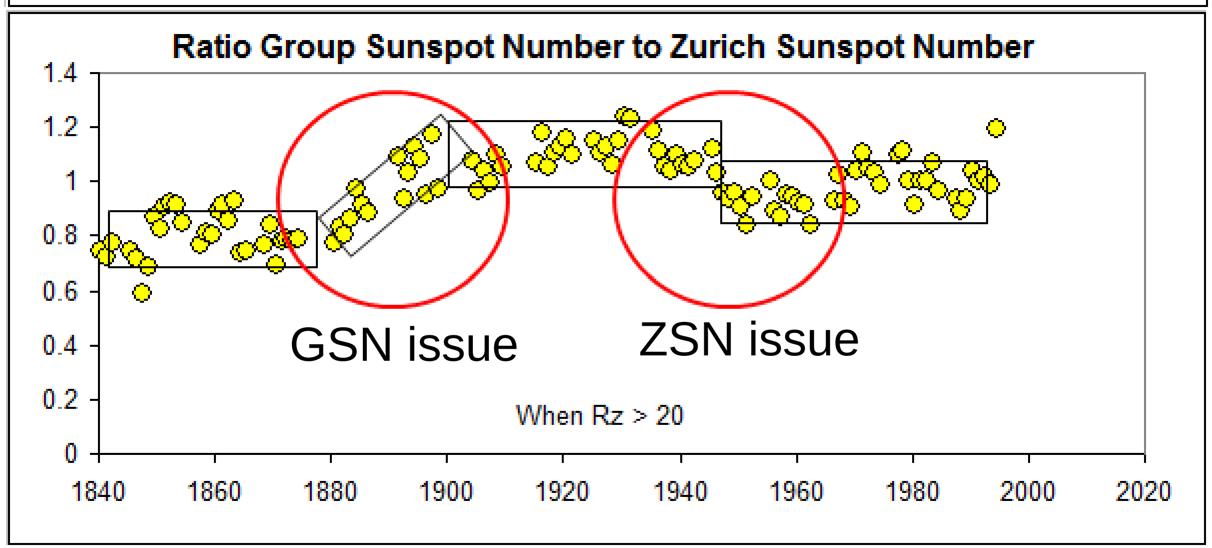
Wolfer & Brunner





How About the Group Sunspot Number?





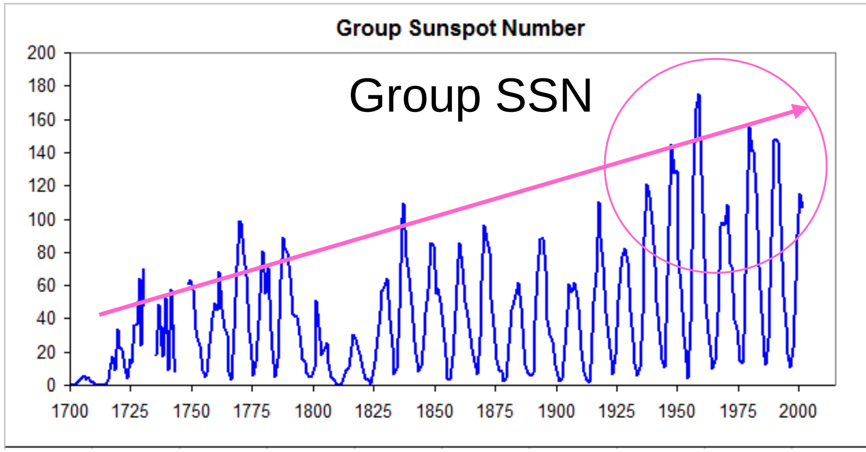
The main issue with the GSN is a change relative to the ZSN during 1880-1900. This is mainly caused by a drift in the reference count of the standard (Royal Greenwich Observatory)

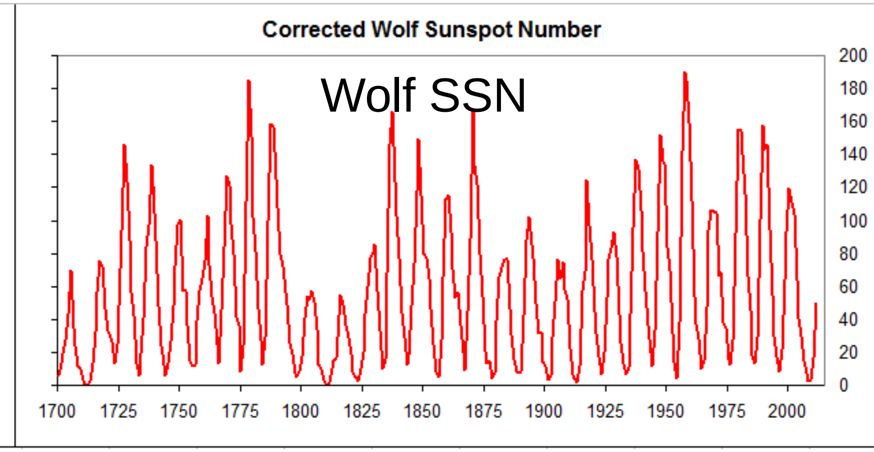
The ratio between the Group Sunspot Number reveals two major problem areas. We can now identify the cause of each

The Tale of Two Sunspot Numbers

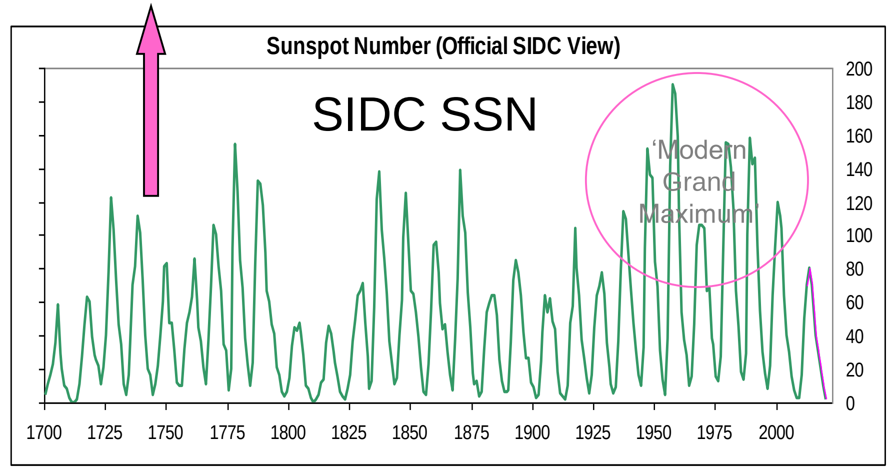
GSN = 12 * Groups

WSN = 10 * Groups + Spots





The 'official' sunspot number [maintained by SIDC in Brussels] also shows a clear 'Modern Maximum' in the last half of the 20th century.



The official record is artificially inflated after 1945 when Max Waldmeier became director of the Zurich Observatory

And suggest that there likely was no Modern Grand Maximum

The Sunspot Workshops I-IV

Figure 5: Participants at the 4th SN Workshop, Locarno, Switzerland, 19-23 May 2014. Left to right: R. Ramelli, F. Marenzi, C. Kiess, D. Supriya, L. Belluzzi, G. Travaglini, R. Howe, C. Fröhlich, T. Dudok de Wit, J. Vaquero, P. Hejda, J. Beer, R. Arlt, J. Stenflo, M. Bianda, L. Svalgaard, S. Cortesi, D. Willis, E. Cliver, O. Hérent, L. Lefèvre, A. Kilcik, A. Bulling, J. Alvestad, F. Clette, J. Javaraiah.

A revised Sunspot Number to be announced at IAU Assembly in August, 2015

Abstract

When Marconi in 1902 demonstrated that radio communication across the Atlantic Ocean at a distance of 2000 miles it became clear that an electric 'mirror' existed high in the atmosphere to guide the radio waves around the curvature of the Earth. Kennelly and Heaviside independently suggested that a layer of ionized gas, the 'ionosphere' at an altitude of 60-100 miles was responsible for the effect, but it was only more than two decades later that the existence of such a layer was firmly established by the British scientist Appelton for which he received the 1947 Nobel Prize in Physics. Physicists long resisted the idea of the reflecting layer because it would require total internal reflection, which in turn would require that the speed of light in the ionosphere would be greater than in the atmosphere below it. It was an example of where the more physics you knew, the surer you were that it couldn't happen. However, there are two velocities of light to consider: the phase velocity and the group velocity. The phase velocity for radio waves in the ionosphere is indeed greater than the Special Relativity speed limit making total internal reflection possible, enabling the ionosphere to reflect radio waves. Within a conducting layer electric currents can flow. The existence of such currents was postulated as early as 1882 by Balfour Stewart to explain a the diurnal variation [discovered in 1722] of the Earth's magnetic field as due to the magnetic effect of electric currents flowing in the high atmosphere, such currents arising from electromotive forces generated by periodic (daily) movements of an electrically conducting layer across the Earth's permanent magnetic field. Today, we know that solar Extreme Ultraviolet radiation is responsible for ionizing the air and that therefore the ionospheric conductivity varies with the solar cycle [e.g. as expressed by the number of sunspots]; so, observations of the Sun are vital in monitoring and predicting radio communications for Amateurs and Professional alike. Conversely, centuries-long monitoring of variations of the Earth's magnetic field can be used to determine long-term variations of solar activity. The talk weaves these various threads from multiple scientific and engineering disciplines together to show the unity of scientific endeavor and its importance for our technological civilization.