Radio Wave Propagation

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What We're Going to Cover

- Part 1
  - A. History of Solar and Ionospheric Studies
  - B. Formation of the Ionosphere
  - C. Measuring the Ionosphere
  - D. Physics of Propagation from 150 KHz to 54 MHz
- Part 2
  - A. Propagation Examples at LF, MF, HF, VHF
  - B. Propagation Predictions
- Part 3
  - A. Disturbances to Propagation
  - B. Interpreting Space Weather
  - C. Solar Cycles
- Additional Info and Books for Your Library

Part 1A
History of Solar and Ionospheric Studies

Solar Studies

- Chinese observed sunspots over 2000 years ago
- Galileo invented the telescope in 1610
  - In 1613 Galileo wrote ". . . I am at last convinced that the spots are objects close to the surface of the solar globe . . ."
- In 1843 Schwabe concluded that sunspots came and went in a periodic fashion
- In 1914 Hale discovered that sunspots are engulfed in whirling masses of gas and that they are surrounded by magnetic fields

Solar Studies

- Wolf devised a method to describe relative sunspot activity in terms of a common standard
  - Sunspot number R = k (10 g + f)
    - g is observed number of sunspot groups
    - f is total number of sunspots
    - k is factor that brings observations of many different observers into general agreement
    - weighted towards groups
  - Subjective measurement
- In the 1930s Pettit found a direct relationship between the sunspot number and the intensity of ultraviolet radiation from the Sun

Solar Studies

- Schwabe credited with discovering the ~ 11-year cycle
- Hale credited with discovering the ~ 22-year cycle
  - Magnetic field of Sun reverses every cycle
- Gleissberg credited with discovering the ~ 88-year cycle
  - We'll see this one later
- Other cyclic periods seen and named for their discoverer

Ionospheric Studies

- Hertz demonstrated that the direction of travel of an electromagnetic wave can be altered by an electrically conductive obstacle
- In 1901 Marconi heard transmissions in Newfoundland from Poldhu (England)
- In 1902 Kennelly (US) and Heaviside (Great Britain) suggested independently that the Earth's upper atmosphere consisted of an electrically conductive region
  - In 1925 Russell proposed the name Kennelly-Heaviside layer
  - In 1926 Watson-Watt introduced the term "ionosphere"

Ionospheric Studies

- In 1924 Appleton found conclusive evidence of an electrically conductive region by measuring the angle of arrival of radio waves from a nearby transmitter
- In 1925 Breit and Tuve demonstrated the existence in a more striking way
  - They transmitted short bursts of energy straight up and measured the delay of the return echo
  - Later they varied the frequency of the transmitted pulses and noted that above a certain "critical frequency" the region would no longer return an echo
  - This was the first documented use of a vertical incidence ionospheric sounder (ionosonde)

Ionospheric Studies

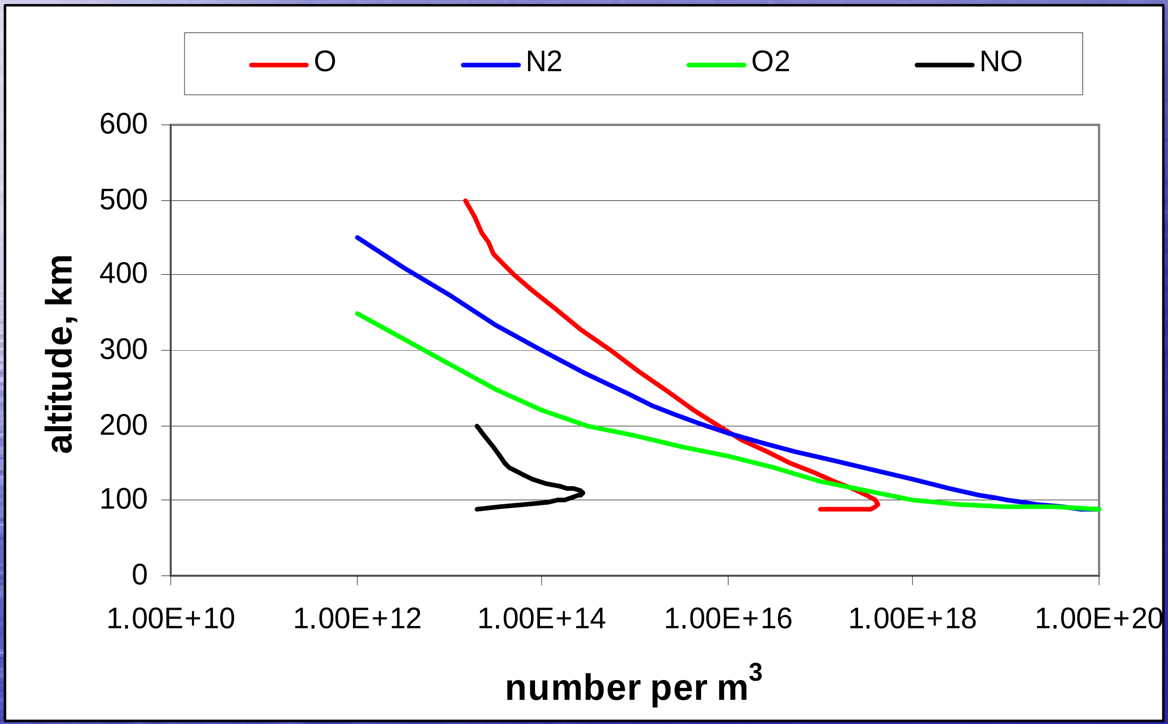
- The work of Breit and Tuve opened the doors
- Swept-frequency ionosondes developed
- Lots of military interest in the ionosphere during WW2
- International Geophysical Year (IGY) from July 1957 – December 1958 performed worldwide measurements of the ionosphere
- Data from worldwide ionosondes allowed development of model of E and F regions

Part 1B
Formation of the Ionosphere

Two Competing Processes

- The electron density in the ionosphere depends on two competing processes
  - Electron production
    - In the F_2 region, atomic oxygen is important for electron production
  - Electron loss
    - In the F_2 region, molecular oxygen and molecular nitrogen contribute to electron loss
- Initiated by solar radiation
  - But other factors also determine ultimate ionization
    - We'll see these in the Propagation Predictions session

Atmospheric Constituents



- 78.1% nitrogen
- 20.9% oxygen
- 1% other gases

- Atomic oxygen dominates above about 200 km

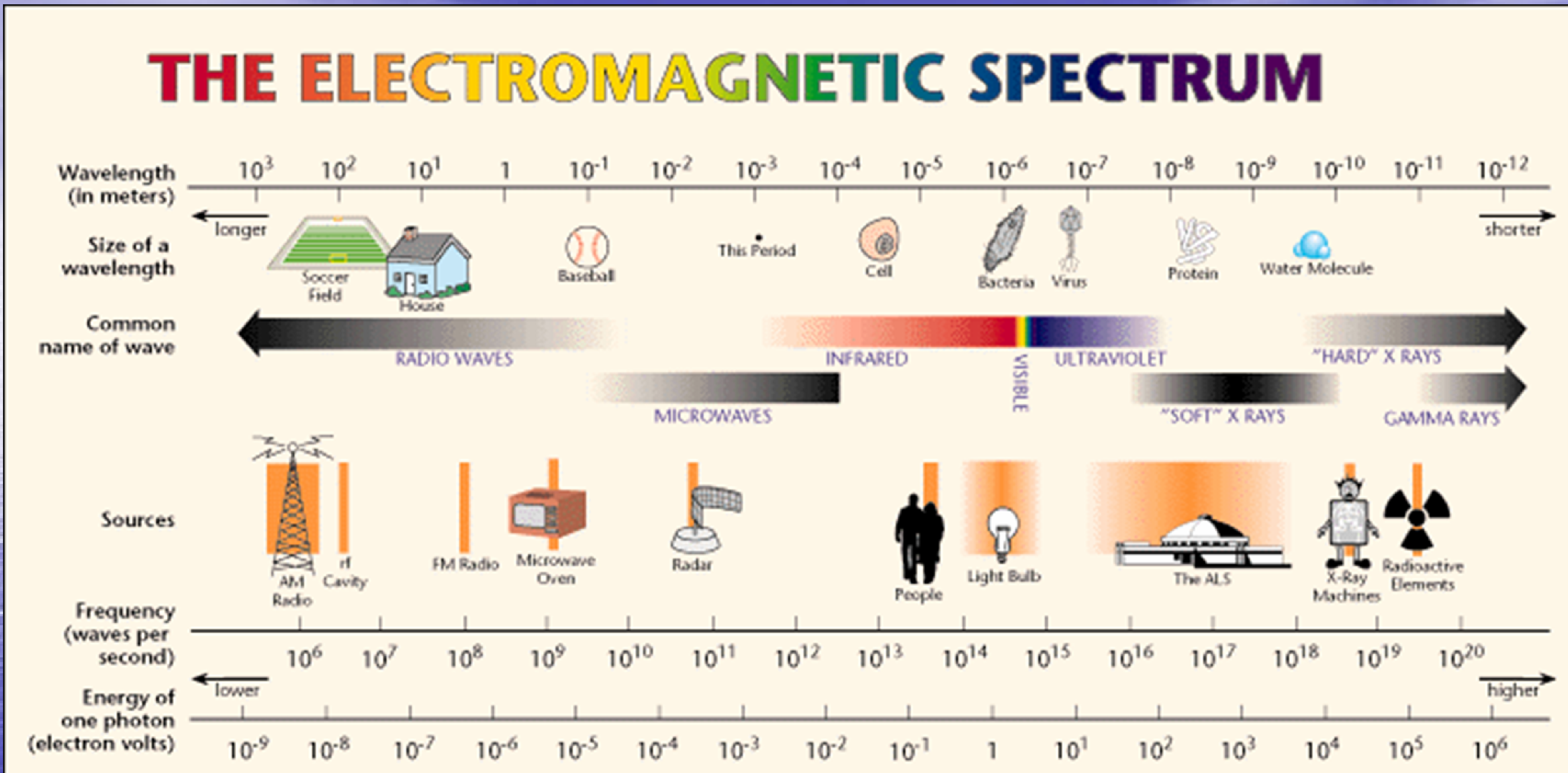
- Nitric oxide is a big player at low altitudes (D region and lower E region)

Maximum Wavelength

	ionization potential	maximum wavelength
O (atomic oxygen)	13.61 eV	91.1 nm
O_2 (molecular oxygen)	12.08 eV	102.7 nm
N_2 (molecular nitrogen)	15.58 eV	79.6 nm
NO (nitric oxide)	9.25 eV	134 nm

- Maximum wavelength is longest wavelength of radiation that can cause ionization
  – Related to ionization potential through Planck's Constant

energy is proportional to frequency
or
energy is proportional to one over the wavelength



HF bands

10.7 cm
solar flux

visible light

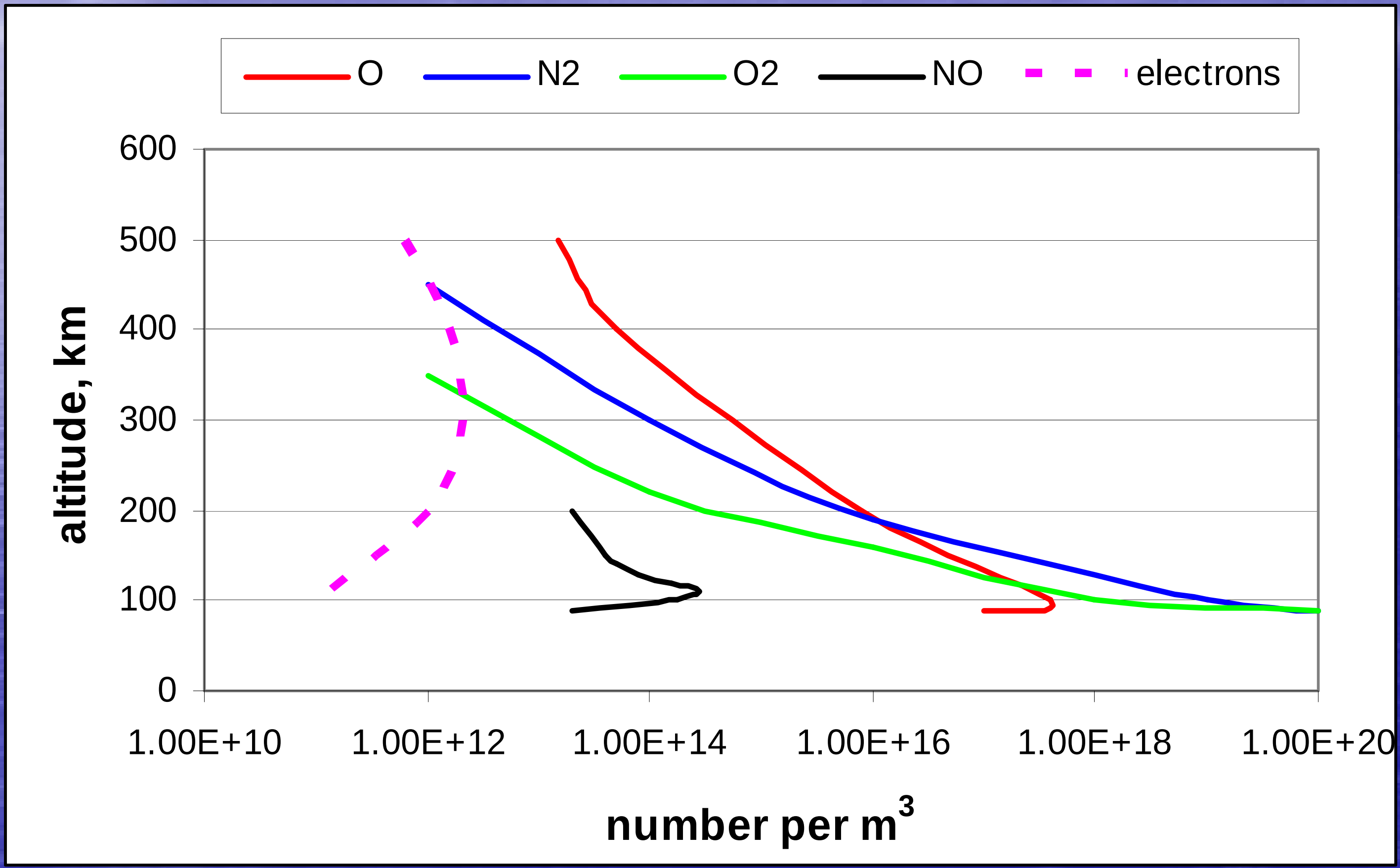
Ionizing radiation

Ionization Process

- As the Sun's radiation progresses down through the atmosphere, it is absorbed by the aforementioned species in the process of ionization
  - Energy reduced as it proceeds lower
  - Need higher energy radiation (shorter wavelengths) to get lower
- True ionizing radiation
  - 10 to 100 nm to ionize O, NO, O_2, N_2 in the F region
  - 1 to 10 nm to ionize O_2, NO in the E region
  - .1 to 1 nm to ionize O_2, N_2 in the D region
  - 121.5 nm to ionize NO in the D region
    - Window in absorption coefficient of atmosphere at 121.5 nm that allows 121.5 nm to pass through down to low altitudes

Sunspots and 10.7 cm solar flux are proxies for the true ionizing radiation

Atmosphere Is Lightly Ionized



Part 1C

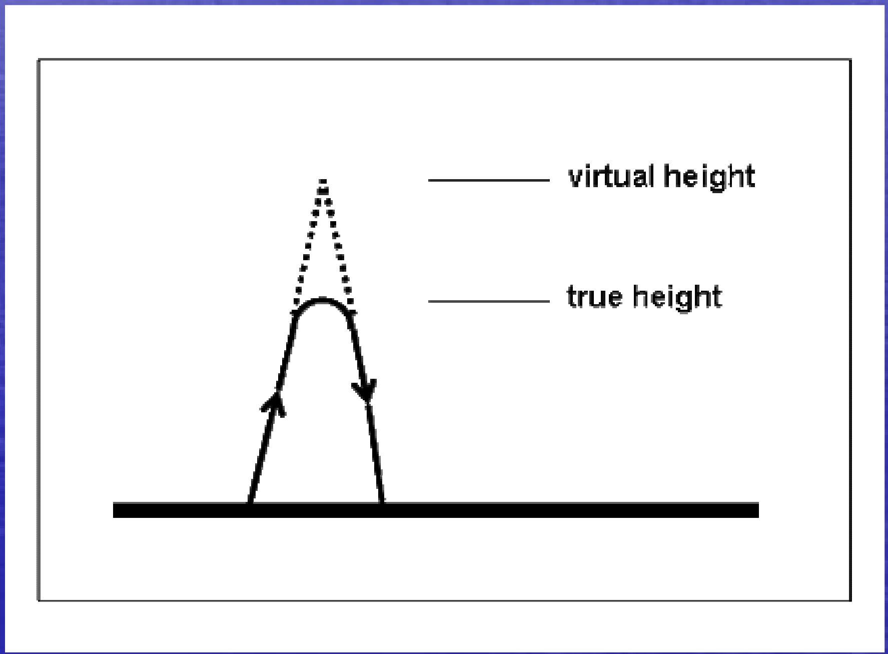
Measuring the Ionosphere

Introduction to Ionosondes

- To make predictions, you need a model of the ionosphere
- Model developed from ionosonde data
- Most ionosondes are equivalent to swept-frequency radars that look straight up
  - Co-located transmitter and receiver
  - Also referred to as vertical ionosondes or vertically-incident ionosondes
- There are also oblique ionosondes
  - Transmitter and receiver separated
  - Evaluate a specific path

What Does an Ionosonde Measure?

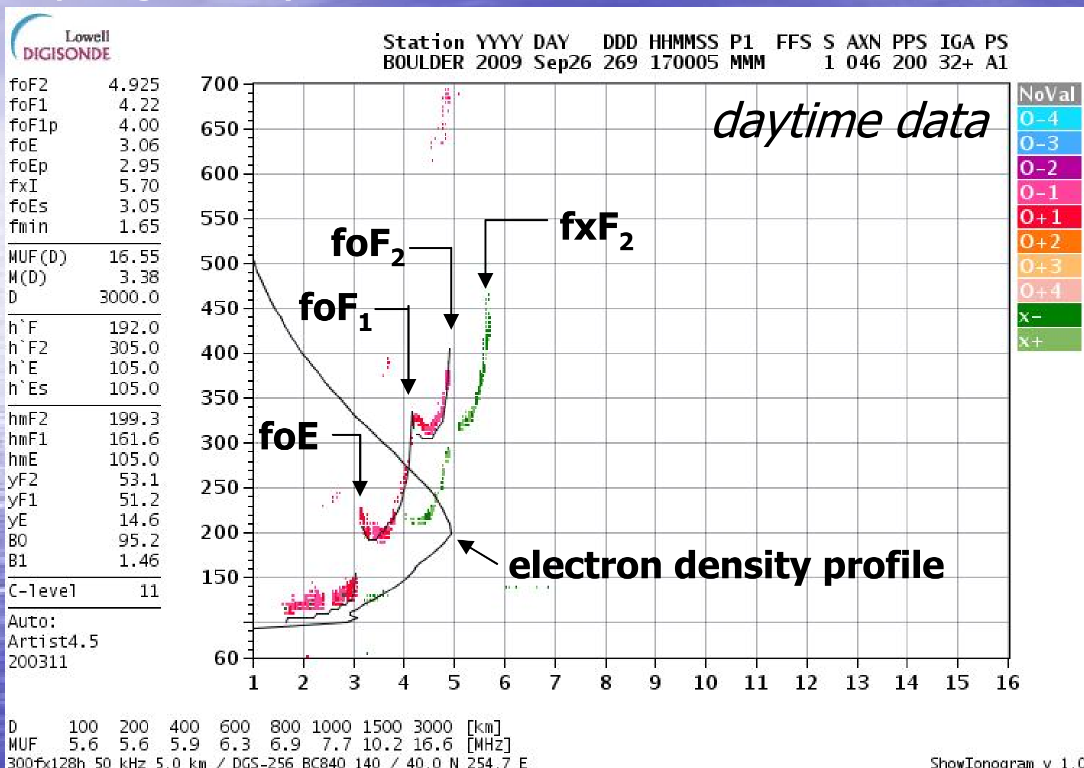
- It measures the time for a wave to go up, to be turned around, and to come back down
- Thus the measurement is time, not height
- This translates to <u>virtual</u> height assuming the speed of light and mirror-like reflection
- The real wave does not get as high as the virtual height



An ionosonde measures <u>time of flight</u>, not altitude, at each frequency

Sample Ionogram

http://digisonde.haystack.edu



- E region and F_2 region have maximums in electron density
- F_1 region is inflection point in electron density
- D region not measured
- Nighttime data only consists of F_2 region and sporadic E due to TX ERP and RX sensitivity (lower limit is ~2 MHz)

- Red is ordinary wave, green is extraordinary wave
- Critical frequencies are highest frequencies that are returned to Earth from each region at vertical incidence
- Electron density profile is derived from the ordinary wave data (along with assumptions about region thickness)
  - Electron density anywhere in the ionosphere is equivalent to a plasma frequency through the equation f_p (Hz) = 9 x $N^{1/2}$ with N in electrons/m^3

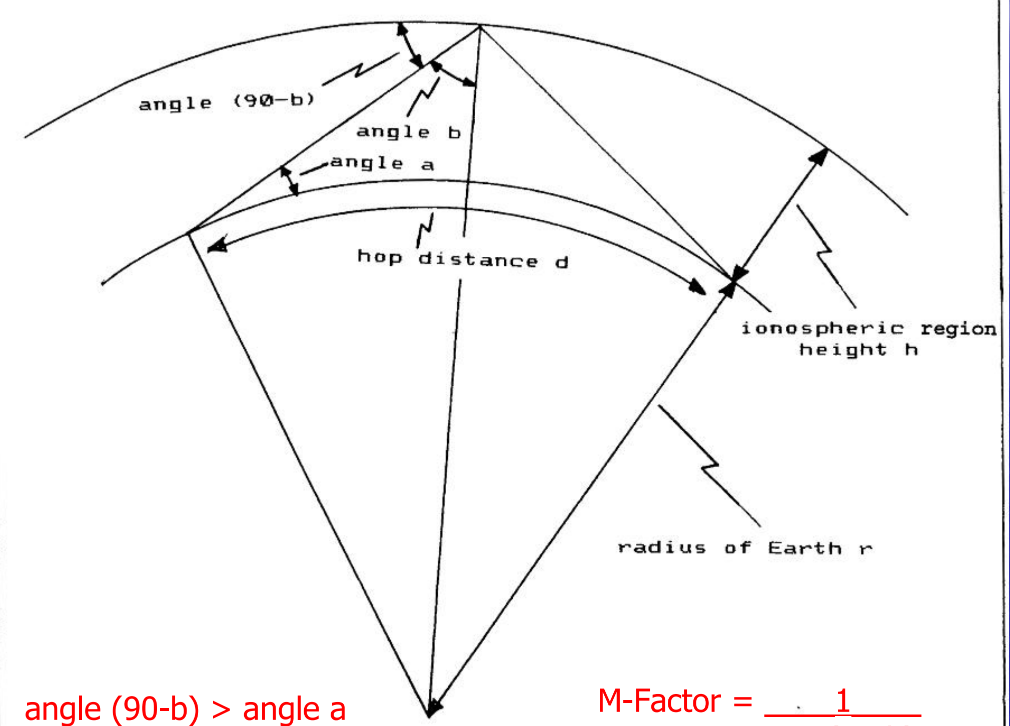
Note that we don't see layers with gaps in between

Characterizing the Ionosphere

- Ionosphere is characterized in terms of critical frequencies (foE, foF_1, foF_2) and heights of maximum electron densities (hmE, hmF_2)
  - 'o' is ordinary, 'x' is extraordinary
  - Easier to use than electron densities
- Allows us to calculate propagation over oblique paths
  - MUF(2000)E = foE x M-Factor for E region
  - MUF(3000)F_2 = foF_2 x M-Factor for F_2 region

Rule of thumb: E region M-Factor ~ 5, F_2 region M-Factor ~ 3

M-Factor Spherical Geometry



angle (90-b) > angle a

$$\text{M-Factor} = \frac{1}{\sin(90-b)}$$

FIGURE 1

M-Factors

height "h"	take-off angle "a"	hop distance "d"	angle of incidence "90-b"	M-factor
100 km	0 deg	2243 km	10.1 deg	5.7
	5 deg	1389 km	11.3 deg	5.1
	10 deg	927 km	14.2 deg	4.1
300 km	0 deg	3836 km	17.3 deg	3.4
	5 deg	2877 km	17.9 deg	3.3
	10 deg	2193 km	19.9 deg	2.9
400 km	0 deg	4401 km	19.8 deg	3.0
	5 deg	3422 km	20.4 deg	2.9
	10 deg	2687 km	22.1 deg	2.7

F Region

- Model developed from many years of worldwide ionosonde data
- Physical models of the atmosphere also contribute to model
- In summary, lots of good ionosonde data to develop model

E Region

- Data on the daytime E region comes out of the ionogram
- But the E region is under direct solar control
  - Measured daytime data not extremely important because we have a good alternate model that ties the E region to the solar zenith angle
- Problem at night - E region critical frequency is usually below the low-frequency limit of an ionosonde.
- Radars
  - Radars confirm that there is indeed a nighttime valley in the electron density above the E region peak
  - Radars help us understand the E region under disturbed geomagnetic field conditions.
- Physical models help

D Region

- Measuring the D region, whether at night or in the daytime, poses the toughest problem for ionospheric scientists
  - – Ionosondes don't have enough ERP
- Radars and rocket flights fill the gap
- As one would expect from these limited availability techniques, our understanding of the D region and its variability leaves a lot to be desired
  - – Not having a good understanding of the D region (at least not as good as our understanding of the E and F regions) has the biggest impact to propagation on the lower frequencies – where absorption dominates in determining propagation
- Another technique used to deduce D region electron densities
  - – Low frequency energy in an electromagnetic wave generated by a lightning discharge propagates in the Earth-ionosphere waveguide
    - Receiving station can record the spectral characteristics of this propagating energy
    - Vary a model of the D region electron density to match its predicted spectral characteristics to the measured spectral characteristics

Session 1D
Physics of Propagation from 150 KHz to 54 MHz

Three Issues

- If you understand the three issues below, you have a good foundation for understanding propagation across the LF, MF, HF, and VHF bands (150 KHz – 54 MHz)
  - Refraction
    - How much an electromagnetic wave bends
  - Absorption
    - How much an electromagnetic wave is attenuated
  - Polarization
    - How an electromagnetic wave is oriented

Refraction

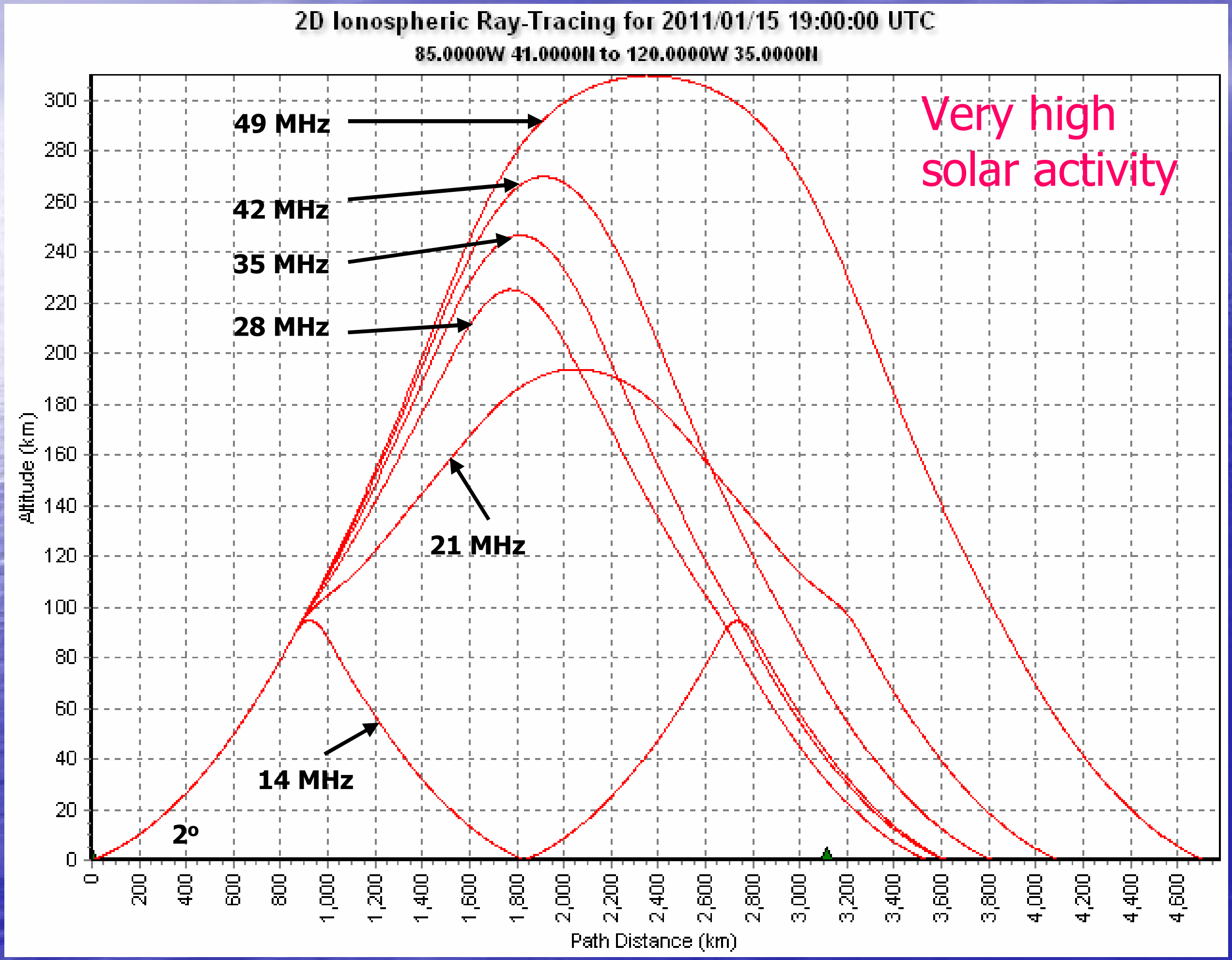
- The amount of refraction is inversely proportional to the square of the frequency

$$\text{Refraction} \sim \frac{1}{f^2}$$

  - The lower the frequency, the more the refraction
    - Don't get as high and thus shorter hops

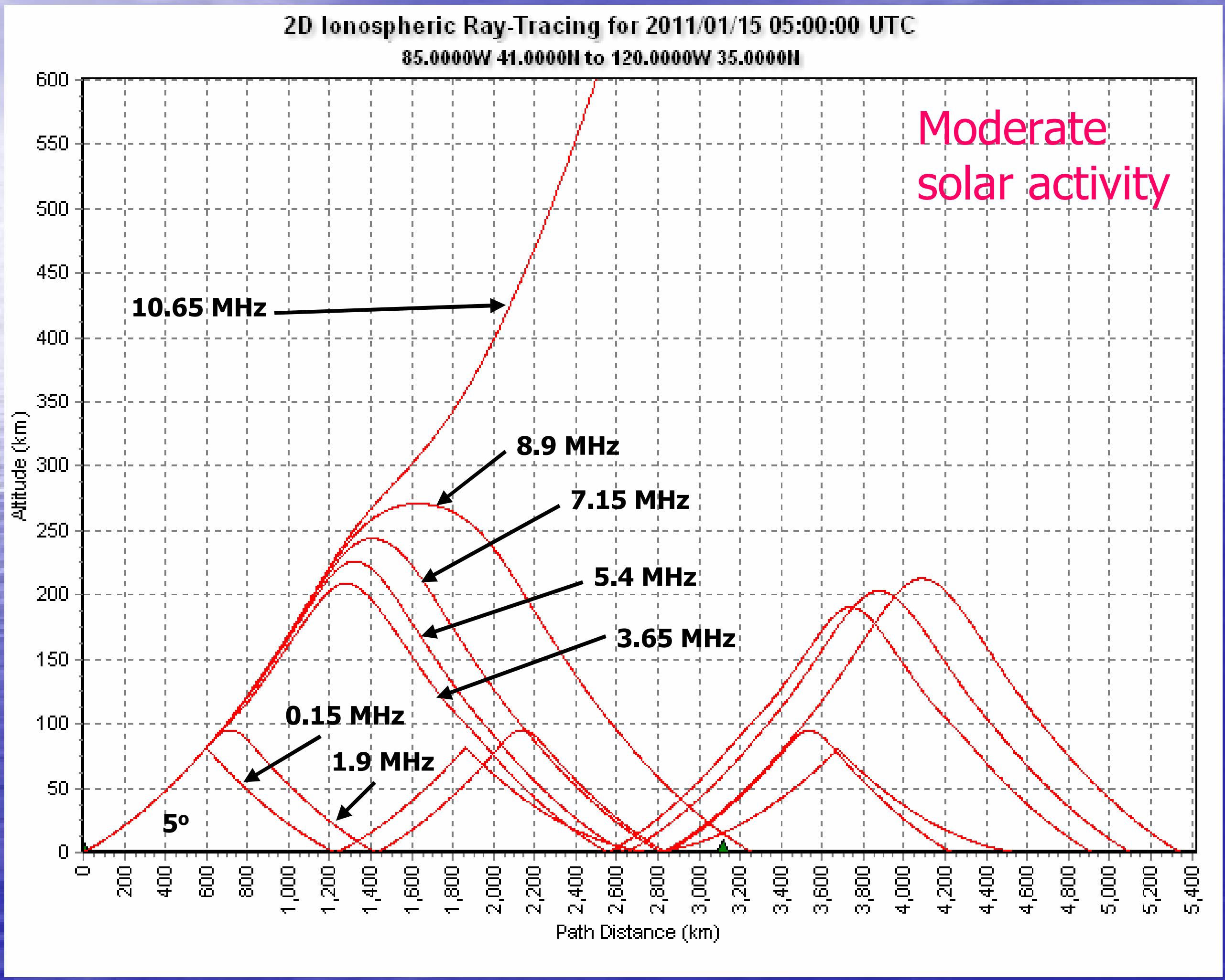
Lower frequencies bend more

Daytime (Noon)



- The lower the frequency, the lower the altitude
- The lower the frequency, the shorter the hop
  - Exception is the ray on 21 MHz due to slight bending by the E region
- Note that 14 MHz at the designated launch angle is refracted by the E region

Nighttime (Midnight)



- The lower the frequency, the lower the altitude
- The lower the frequency, the shorter the hop
- 0.15 MHz (150 KHz) only gets up to about 80 km
  - This is below the absorbing region (lower E region at night)
- 160m at designated launch angle also is refracted by the E region

Absorption

- The amount of absorption is inversely proportional to the square of the frequency

$$\text{Absorption} \sim \frac{1}{f^2}$$

  - The lower the frequency, the more the absorption

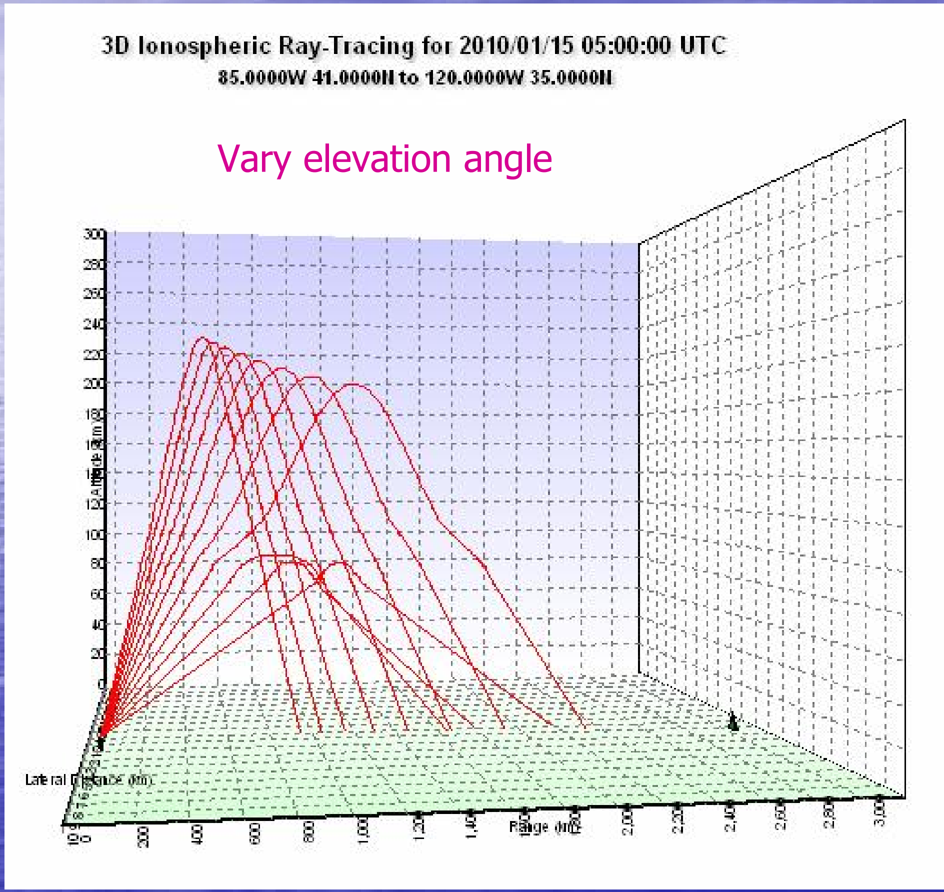
Lower frequencies generally have shorter and more lossy hops

Absorption

Jan 15, midnight, medium solar activity 1500 km F hop		Jan 15, noon, high solar activity 3400 km F hop	
frequency	o-wave absorption	frequency	o-wave absorption
0.15 MHz	4.0 dB	14 MHz	E hop
1.9 MHz	17.8 dB	21 MHz	6.3 dB
3.65 MHz	2.3 dB	28 MHz	2.4 dB
5.4 MHz	0.8 dB	35 MHz	1.4 dB
7.15 MHz	thru ionosphere	42 MHz	0.9 dB

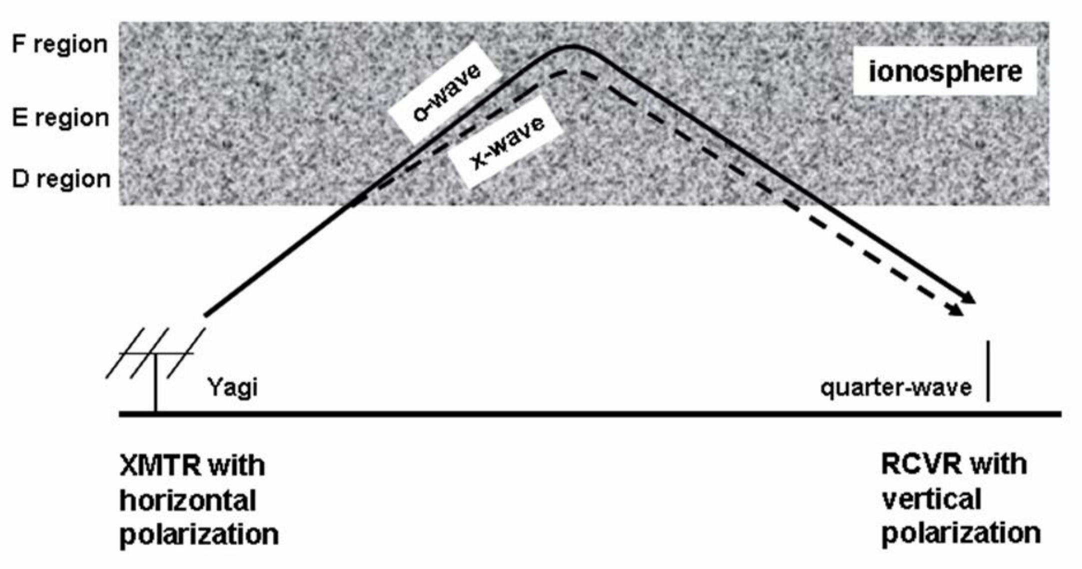
The lower the frequency, the more the absorption – until we go below 160m

160m Ray Tracing at Night



- Extremely low angles are E region hops
  - foE is around 0.4 MHz
    - MUF is 5 x 0.4 = 2 MHz
  - How important are these in our DXing efforts on topband?
- Higher angles go through E region to higher F region
  - Longer hops, less absorption
- Even at solar minimum in the dead of night, 160m RF usually doesn't escape the ionosphere

Polarization



- Polarization of up-going wave from the XMTR to the ionosphere is constant
- Upon entering the ionosphere, the e-m wave excites both an O-wave and X-wave
- O-wave and X-wave propagate through the ionosphere
- Polarizations of the two down-coming characteristic waves are constant from the bottom of the ionosphere to the RCVR.
- The x-wave takes a different path through the ionosphere than the o-wave because the index of refraction is different for the two characteristic waves.
- Strongest signal at the RCVR will come from the characteristic wave that most closely matches the polarization of the RCVR.

160m – 6m

- 160m
  - Polarization is highly elliptical
  - X-wave index of refraction very different
  - X-wave suffers significantly more absorption, so it is usually not considered
  - For those at mid to high latitudes, vertical polarization best couples into the O-wave
- 80m – 6m
  - Circular polarization
  - Both O-wave and X-wave propagate with equal absorption
  - Index of refraction similar, so paths similar

In all cases O-wave and X-wave are orthogonal

Refraction/Reflection/Scatter

- Refraction
  - Electron density gradient much greater than one wavelength
  - Not much absorption
- Reflection
  - Electron density gradient on the order of one wavelength
  - Not much absorption
  - Also known as specular reflection - like a mirror
- Scatter
  - Electron density gradient much less than one wavelength
  - Very lossy

Session 2A

Propagation Examples at LF, MF, HF, VHF

Normal Propagation

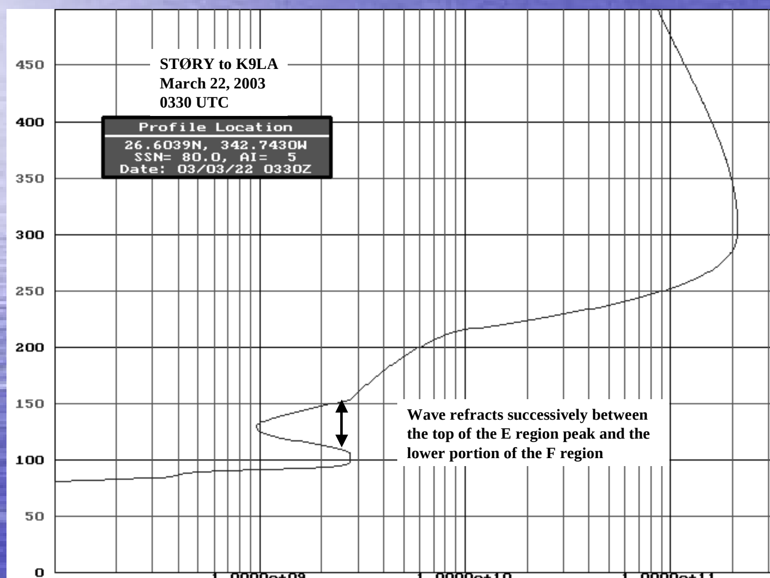
- LF
- MF
- HF - F region
  - Short path
  - Long path
  - Ionosphere-ionosphere modes
- HF – E region
  - Normal
  - Sporadic E
  - Auroral E
- NVIS
- VHF
  - Ducting in the troposphere
  - Sporadic E
  - Aurora

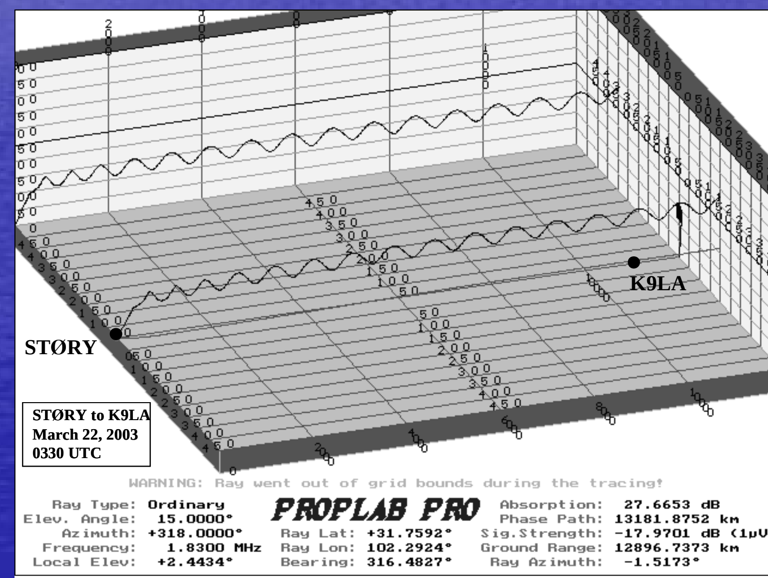
LF: Earth-Ionosphere Wave Guide

- LF doesn't get very high into the ionosphere
  - Refracted at or below the D region
    - Somewhat impervious to disturbances
  - Doesn't get up to the absorbing region
    - D region during the day
    - Lower E region during the night
- LORAN C (navigation) at 100 KHz good example
  - Worldwide propagation
- Antennas are kind of big (and inefficient)
- Noise is a problem

MF: Ducting on 160m

Distances at and greater than 10,000 km on 160m are likely due to ducting in the electron density valley above the nighttime E region peak

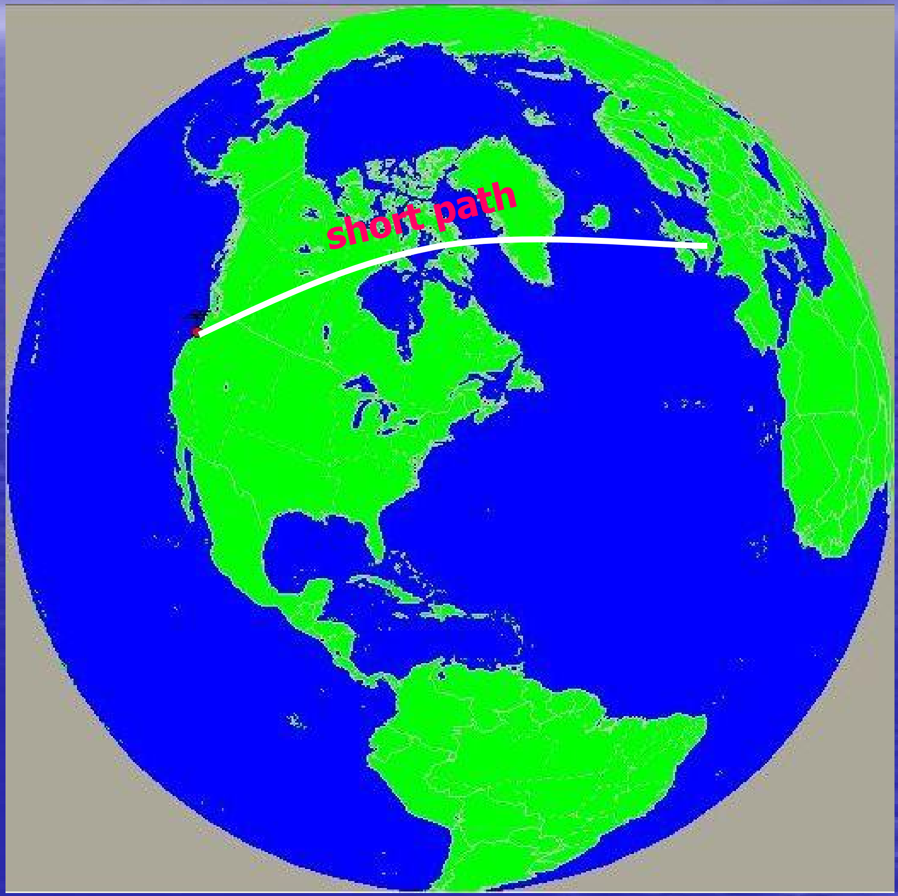




Ducting does not incur loss from multiple transits through the absorbing region and loss from multiple ground reflections

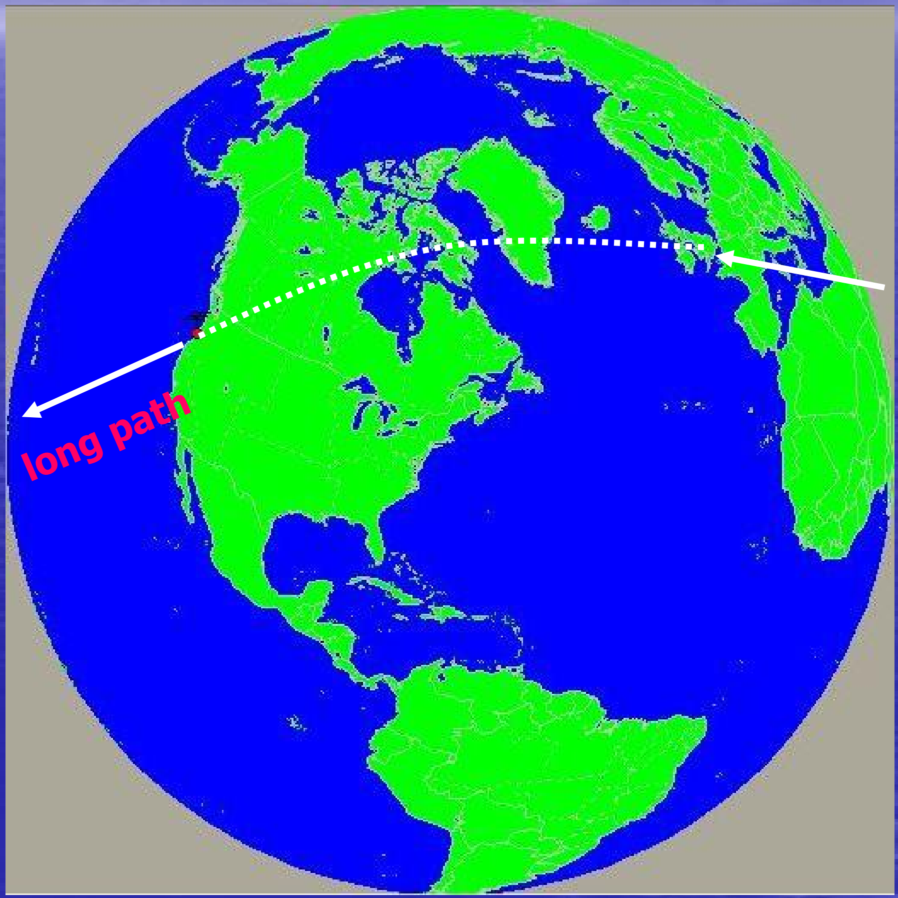
HF: F Region Short Path

- Most of our DXing is multi-hop short path
- To get from Point A to Point B, a great circle route is the shortest distance on a sphere
  - Airliners fly great circle routes
- There are two great circle paths
  - Short path (always less than 20,000 km)
  - Long path (greater than 20,000 km)



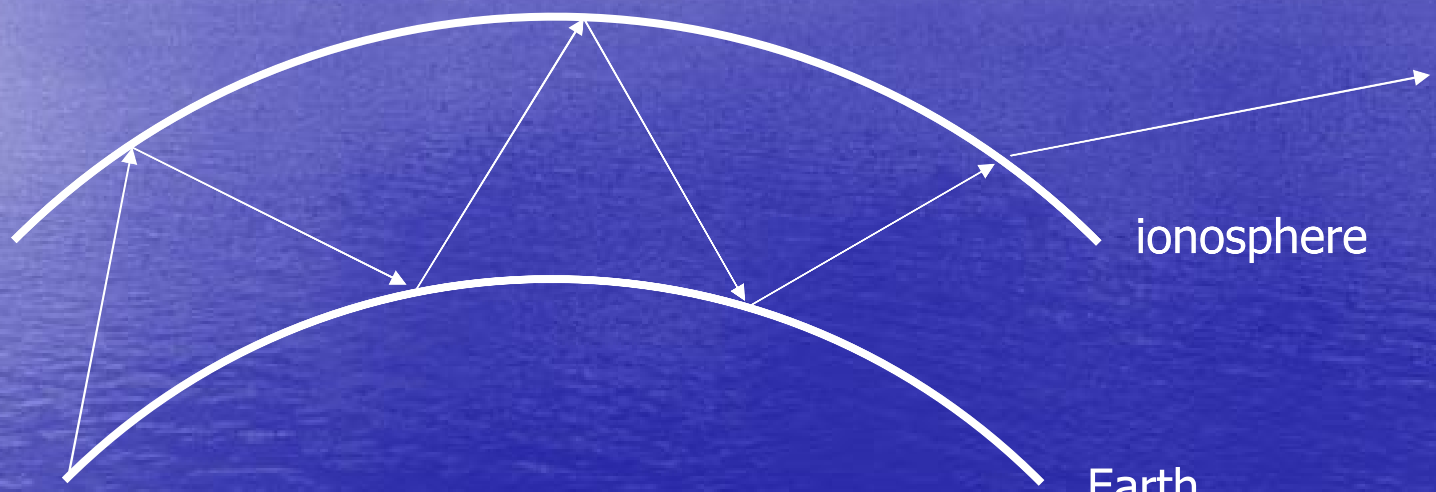
HF: F Region Long Path

- For 15m/12m/10m long path
  - Best months are March through October
  - West Coast
    - After sunset to Mideast and EU
    - After sunrise to VU area (but lack of ops on this end
  -)Bands
    - 15m should be happening now
    - 12m should get better this summer (per Cycle 24's ascent so far)
    - 10m should get better this fall (per Cycle 24's ascent so far)



HF: F Region Ionosphere-Ionosphere Modes

- Multi-hop can have limits



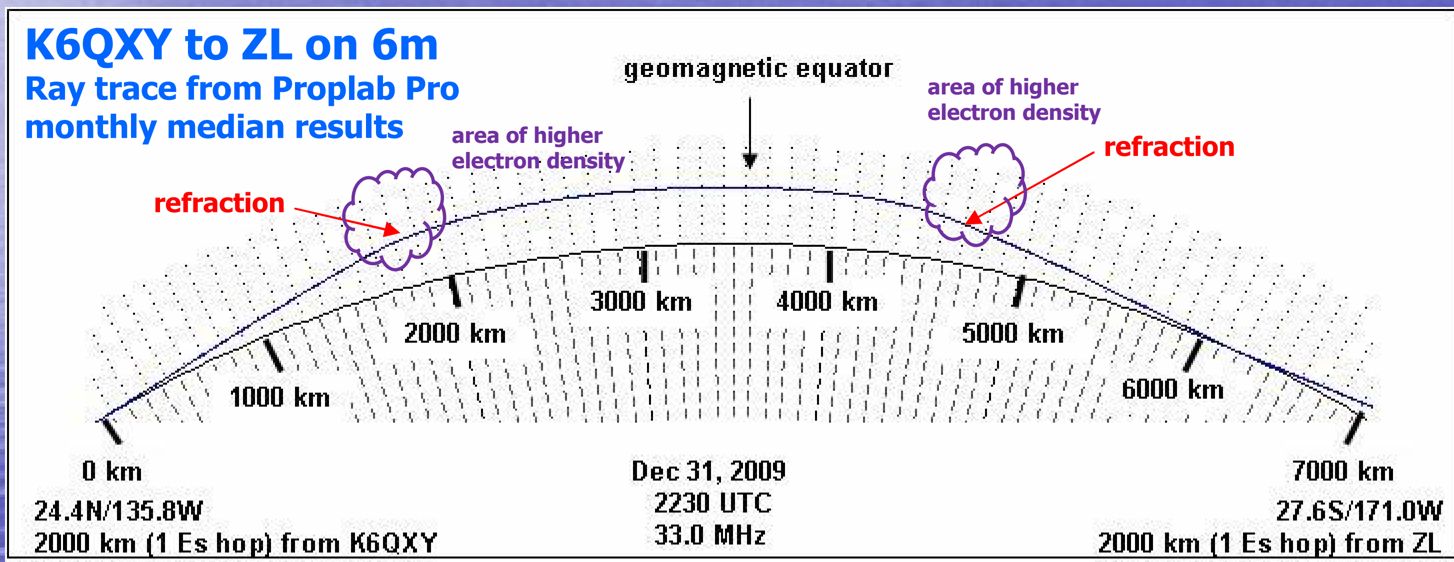
- On the lower bands there may be too much absorption for multi-hop – the signal is too weak
- On the higher bands the MUF may not be high enough to refract the ray back to Earth for multi-hop – the ray goes out into space

Higher MUF & Less Absorption

chordal hop	**unaffected by the ionosphere in between refraction points**
duct	**consecutive refractions between E and F regions**
Pedersen Ray	**high angle ray, close to MUF, parallels the Earth**

Chordal Hop

- Example – TEP (trans-equatorial propagation)



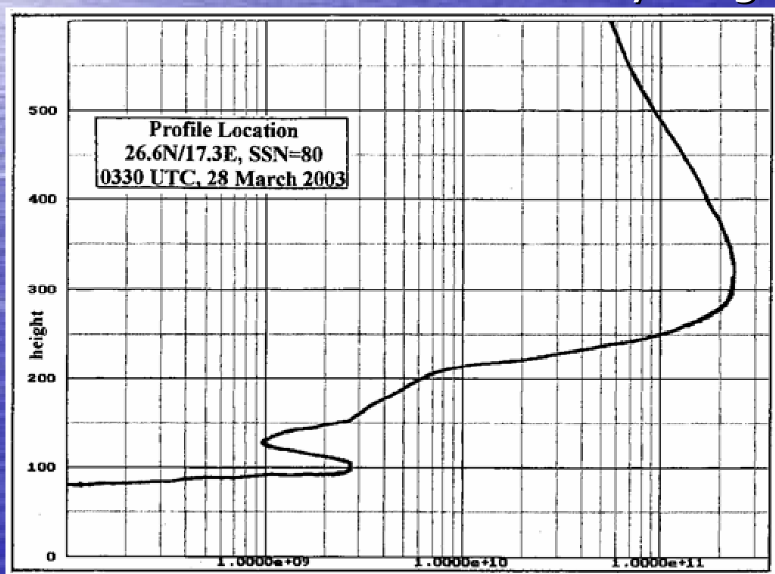
- High density of electrons on either side of geomagnetic equator
- Extremely long hop – approximately twice a normal hop
- Only two transits through the absorbing region
- No ground reflections
- Literature says MUF is approximately 1.5 times normal F_2 hop

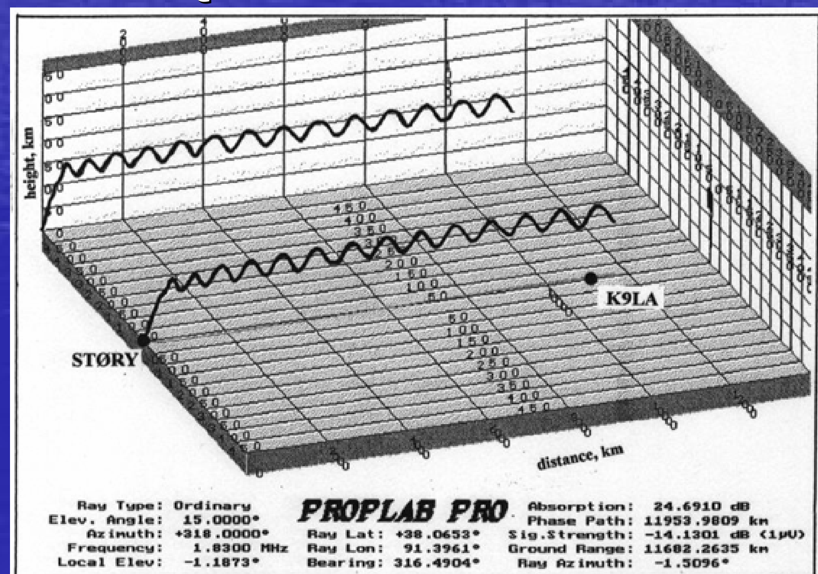
helps MUF and absorption

Duct

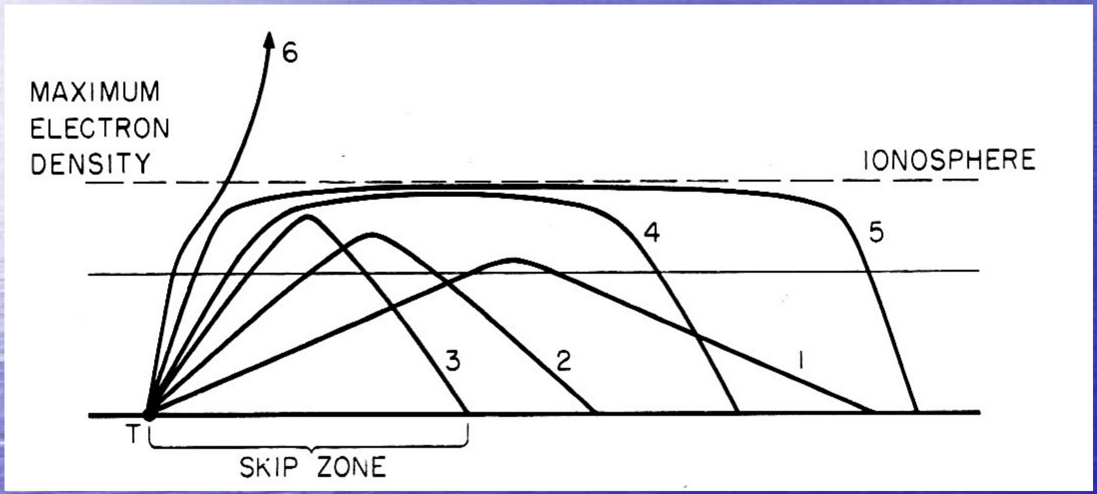
- Requires upper and lower boundary for successive refractions
- Need entry and exit criteria - small range of angles
- No transits through the absorbing region
- No ground reflections
- Low grazing angles with ionosphere – higher MUF
- Believed to allow extremely long distance QSOs on 160m

helps MUF and absorption





Pedersen Ray



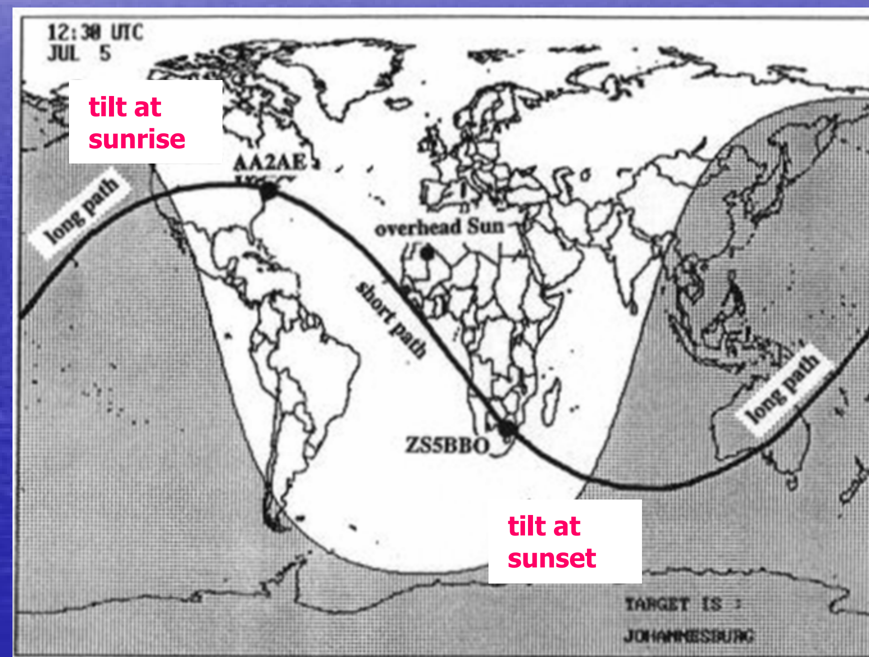
- 1 and 2 are "low-angle" paths
- 3 is "medium-angle" path
- 4 and 5 are "high-angle" Pedersen Ray paths
- 6 goes thru the ionosphere

- Not a lot in the literature on the Pedersen Ray
- Comment from *Ionospheric Radio* (Davies, 1990)
  - Across the North Atlantic, occurrence tends to peak near noon at the midpoint
- One would surmise that the ionosphere needs to be very stable for a ray to exactly parallel the Earth for long distances
- Probably no help with MUF – biggest advantage appears to be with lower absorption due to less transits of the absorbing region and no ground reflection losses

helps absorption

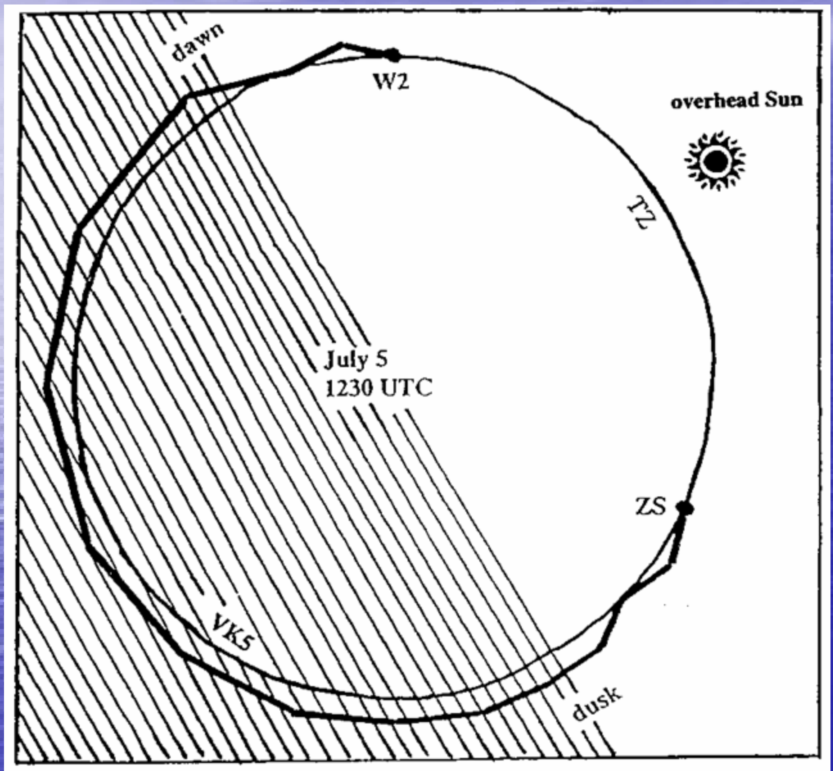
A 20m Example

- K2MO (AA2AE at the time) to ZS5BBO on July 5, 2003 at 1230 UTC on 20m SSB via long path
- K2MO reported that ZS5BBO's signal was around S7 (~ -83 dBm)
- Long path from W2 starts off in daylight, goes into darkness, and ends in daylight
- Short path has high MUF but marginal signal strength due to absorption
- Long path signal strength from ZS predicted to be -125 dBm
  - About 40 dB shy of S7



Short path 12,700 km
Long path 27,300 km

A 20m Example



- The crude picture on the left shows chordal hops as the ionosphere-ionosphere mode
- Proplab Pro data indicates the K2MO-to-ZS5BBO QSO was ducting
- Easier to draw chordal hops!
- You've probably seen a similar picture in the propagation literature.

Ionosphere-ionosphere modes are our friends

HF: E Region

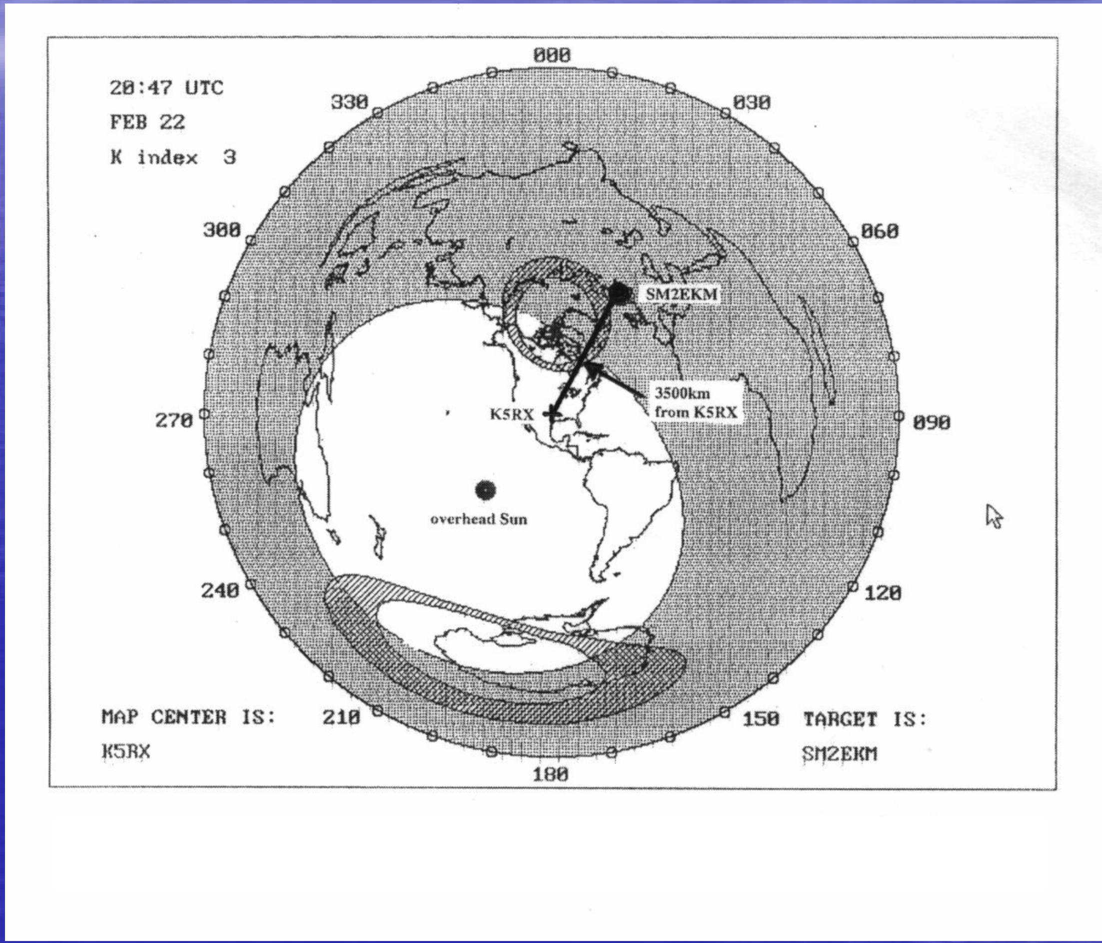
- During the daytime, we can have short-distance propagation up to 14 MHz via the normal E region
  - Shorter hops
  - More total absorption
  - Keeps energy from getting to longer hops in the F region

HF: Sporadic E

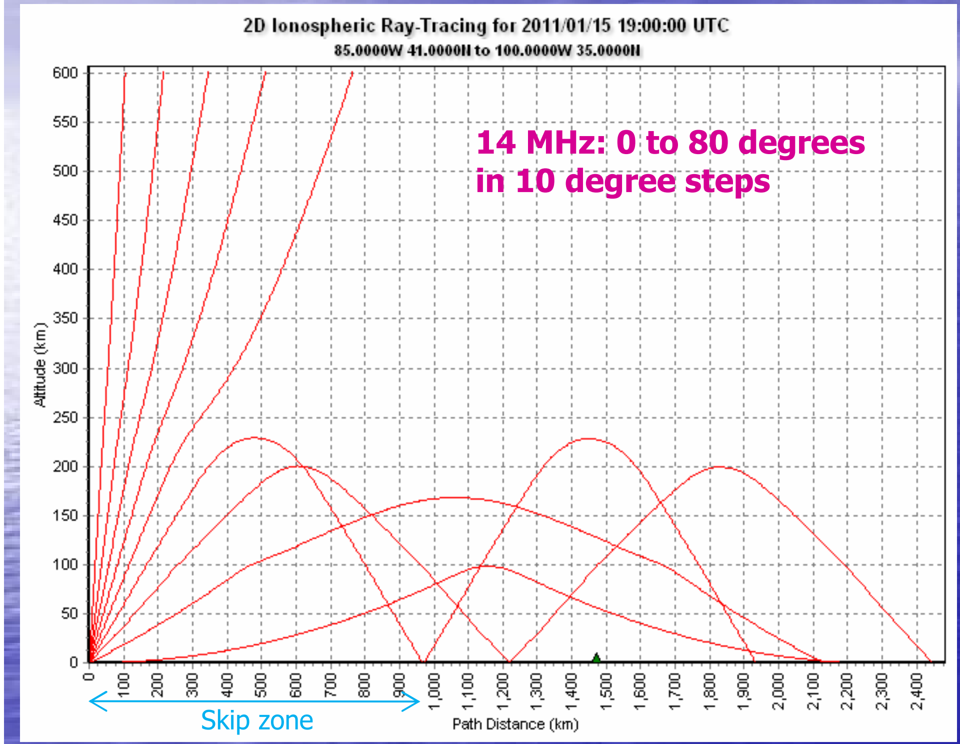
- Sporadic E source is thought to be due to meteor debris and wind shear
- E-skip occurs on 10m – and even 15m
- Not correlated to a solar cycle
- Late morning and early evening in the summer
- Early evening in December
  - Can help the ARRL 10m Contest

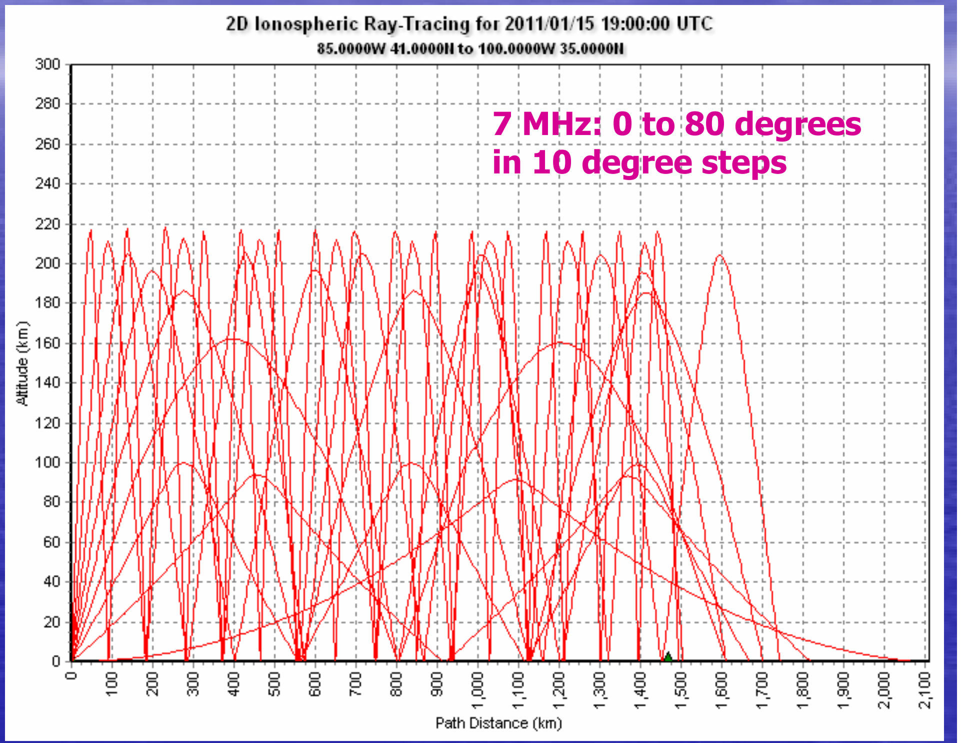
HF: Auroral E

- This appears to be a 15m and 10m phenomenon
- Work Scandinavian countries but can't work EU
- Moderate geomagnetic field activity
- Late afternoon in the fall appears to be most prominent
- Need link to auroral zone – F_2 likely



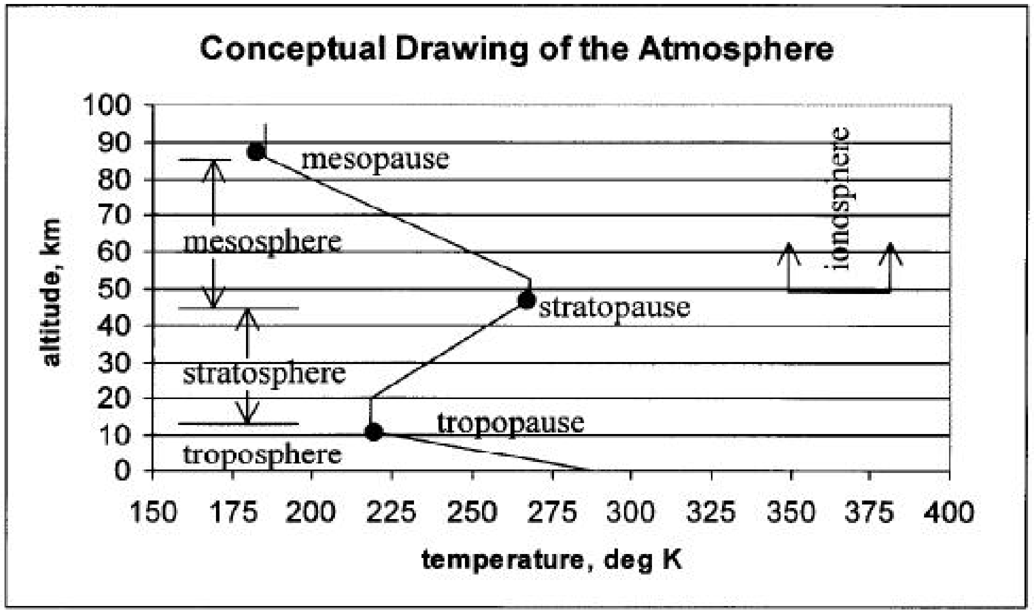
NVIS





- Near Vertical Incidence Skywave
- Higher frequencies have skip zone
- Go lower in frequency
- Use antenna that put most of its energy at higher angles

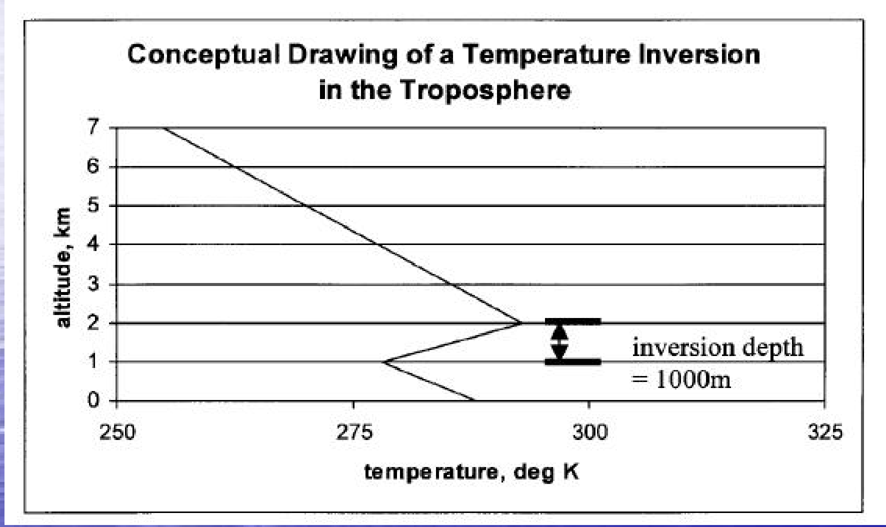
VHF: Ducting in Troposphere

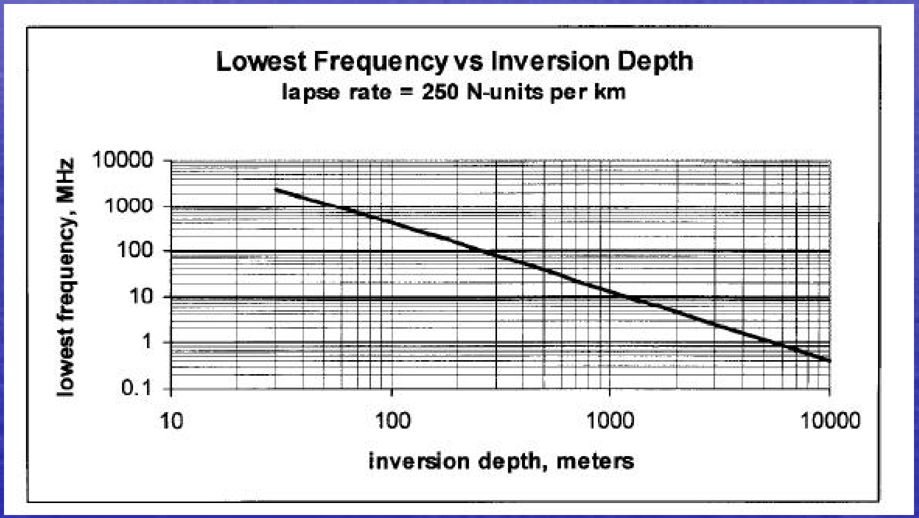


index of refraction = $1 + [77.6 \times P/T + 373200 \times e/T^2] \times 10^{-6}$

If we plug in typical values for P, T, and e at ground level, we'll get about 1.000315. Because this is such a small amount above 1, the term in brackets is defined as N and the refractivity of the atmosphere is defined in terms of N-units. In this example, N =315.

VHF: Ducting in the Troposphere





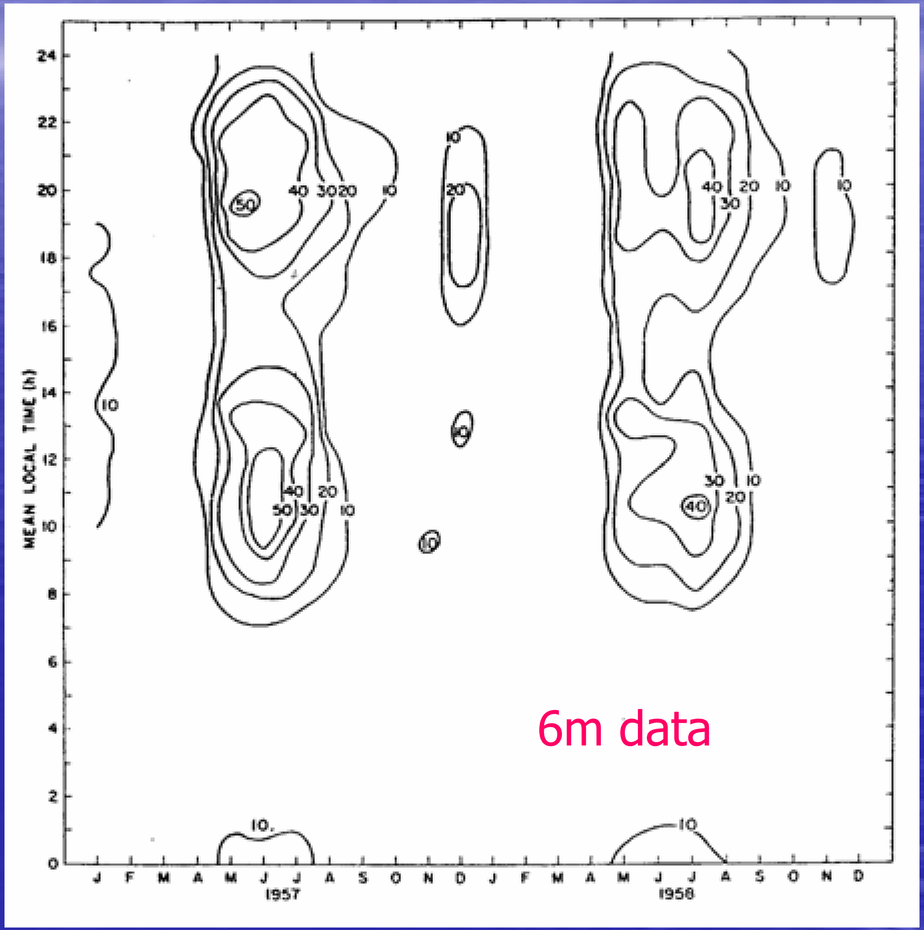
Greatest change in index of refraction occurs in a temperature inversion

Inversion depth limits the lowest frequency than can duct

Inversion depths of 1000 m and greater are rare

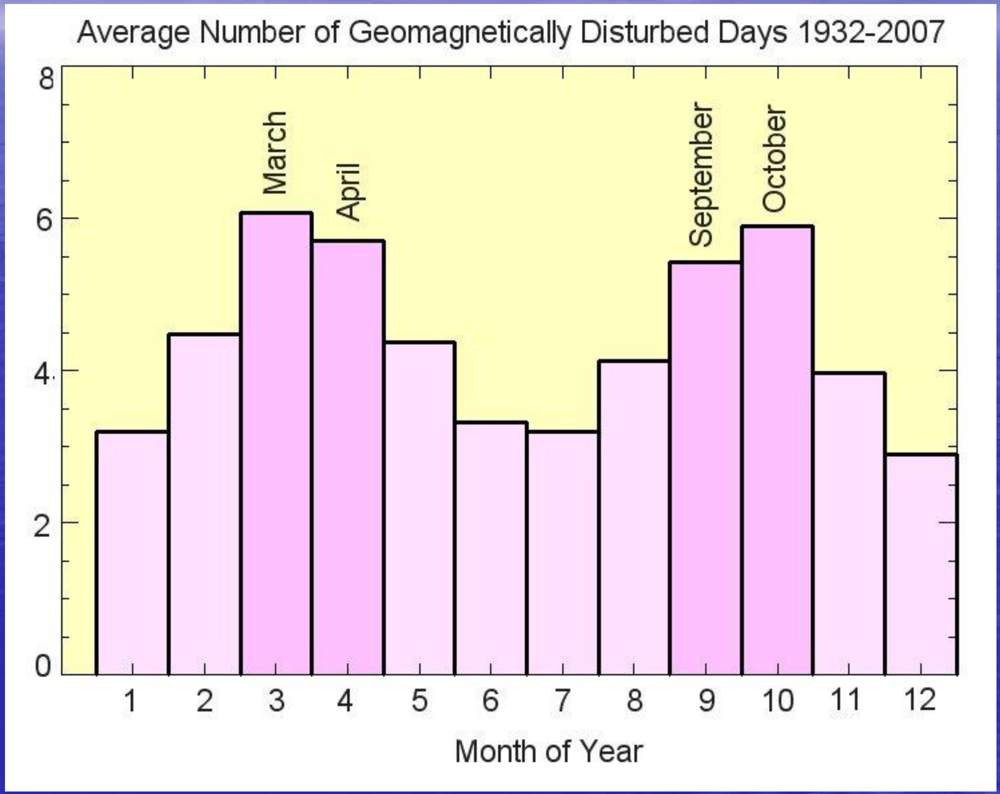
VHF: Sporadic E

- To reiterate, sporadic E appears to be independent of where we are in a solar cycle
- 6m can provide domestic and international QSOs
- Sporadic E can get up to 2m
- Best during summer months
- Secondary peak in December



VHF: Aurora

- When geomagnetic field activity is high, can reflect VHF off the auroral curtain (precipitating electrons)
- Point your Yagi in a northerly direction
- CW is the preferred mode – will be raspy
- Equinoxes are the best months



Unusual Propagation

- Skewed paths
- Scatter paths
- VHF SSSP (summer solstice short path)
  - Due to PMSE (polar mesosphere summer echoes)?
- Drifting patches of F_2 region ionization across the polar cap

Skewed Paths

- Remember that the amount of refraction is inversely proportional to the square of the frequency
  - The lower the frequency, the more the refraction (bending) for a given electron density profile
- Lower frequencies most likely to have skewed paths

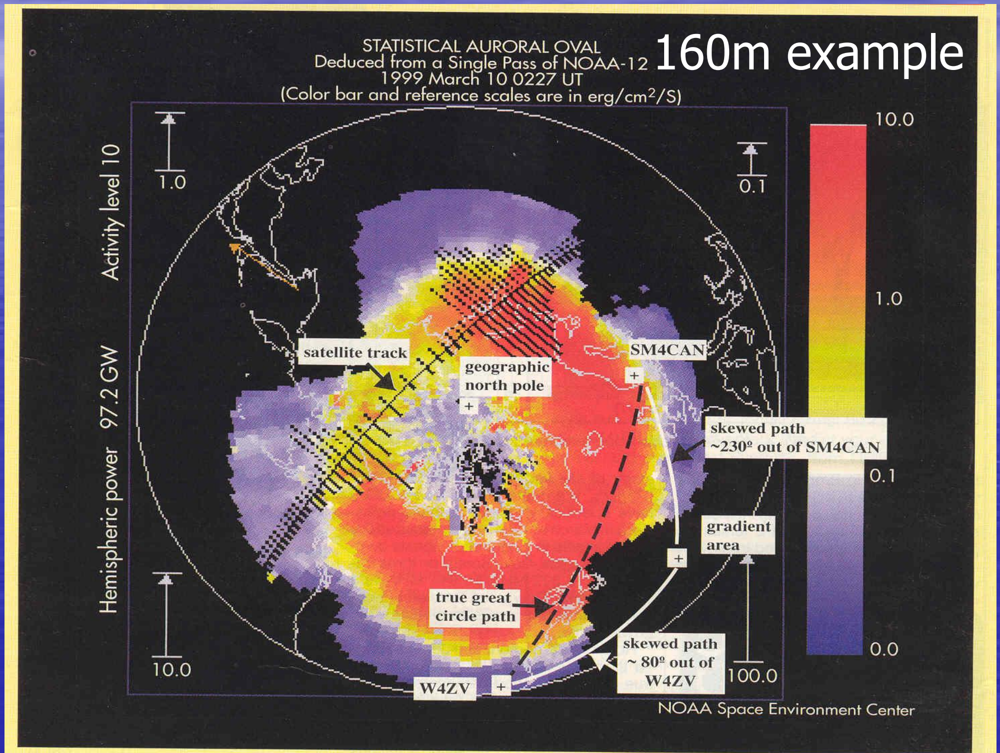
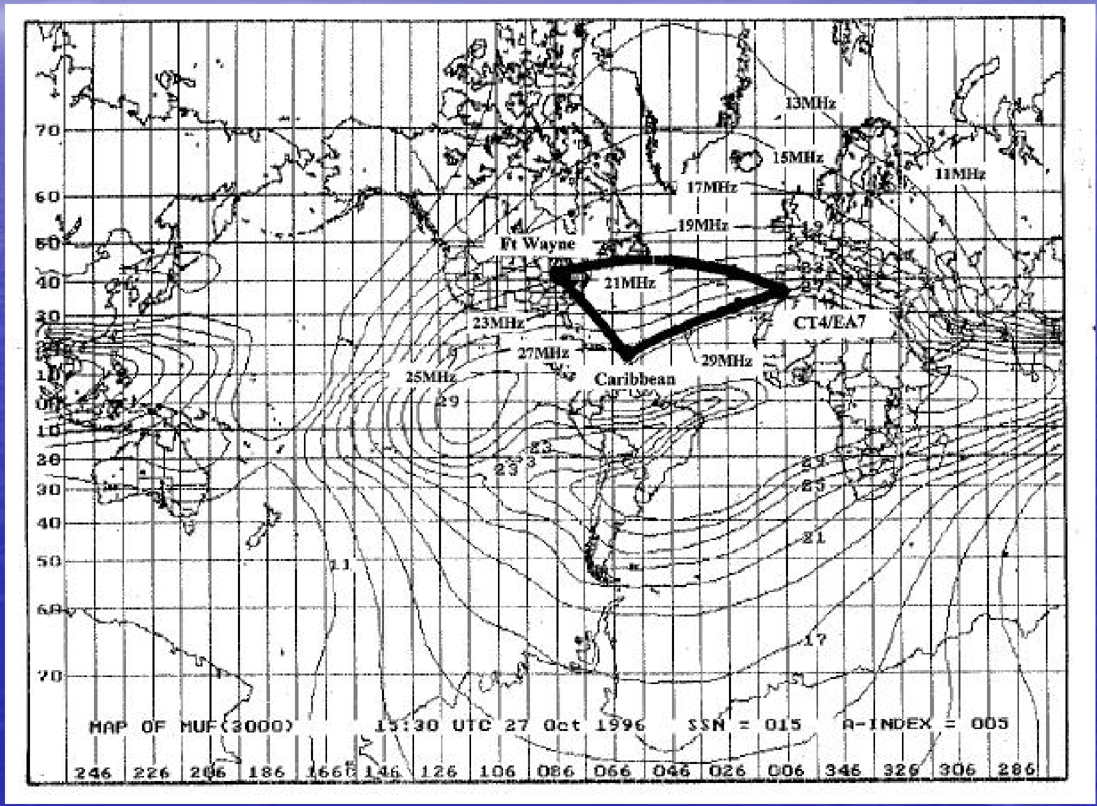


Fig. 3– Satellite photo with auroral oval and W4ZV-to-SM4CAN paths.

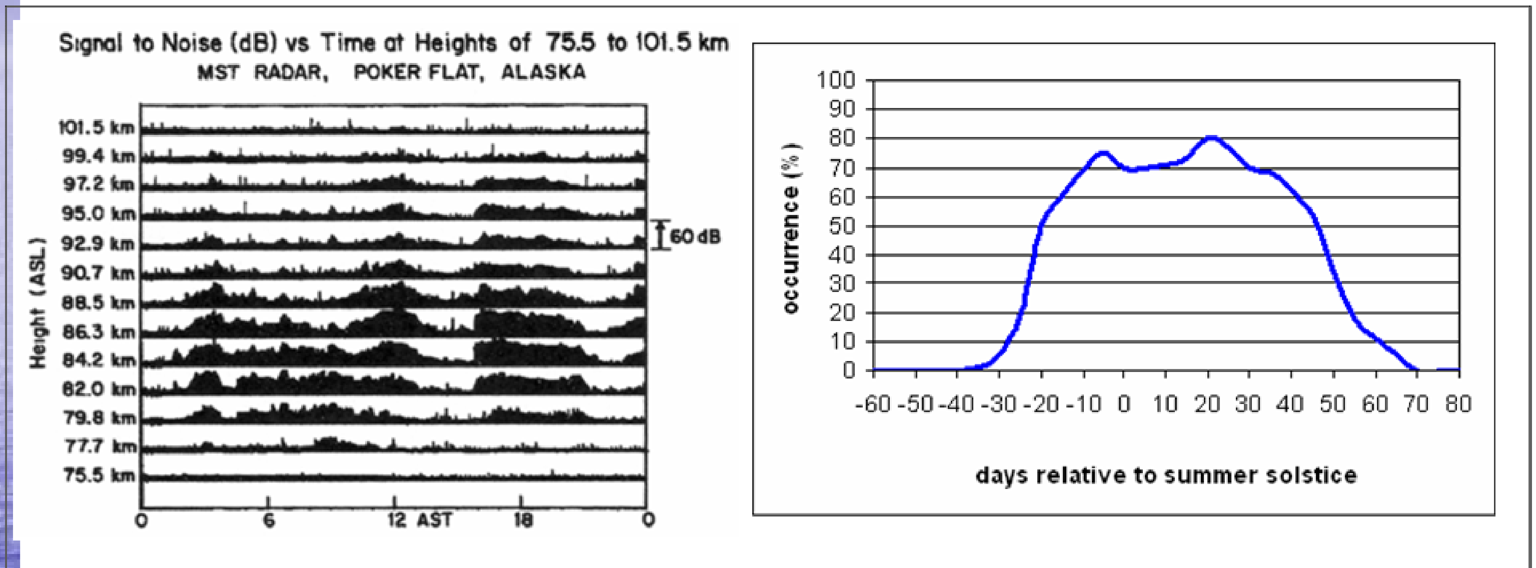
- Why isn't the great circle path open?
- Where is the skew point?
- Why is the skewed path open?

Scatter Paths

- Usually happens when the short path MUF isn't high enough
- Point to a more southerly direction
  - Higher electron densities
- Midwest to EU via the Caribbean
- Midwest to JA via the southwest
- Signals will usually be weak



VHF SSSP



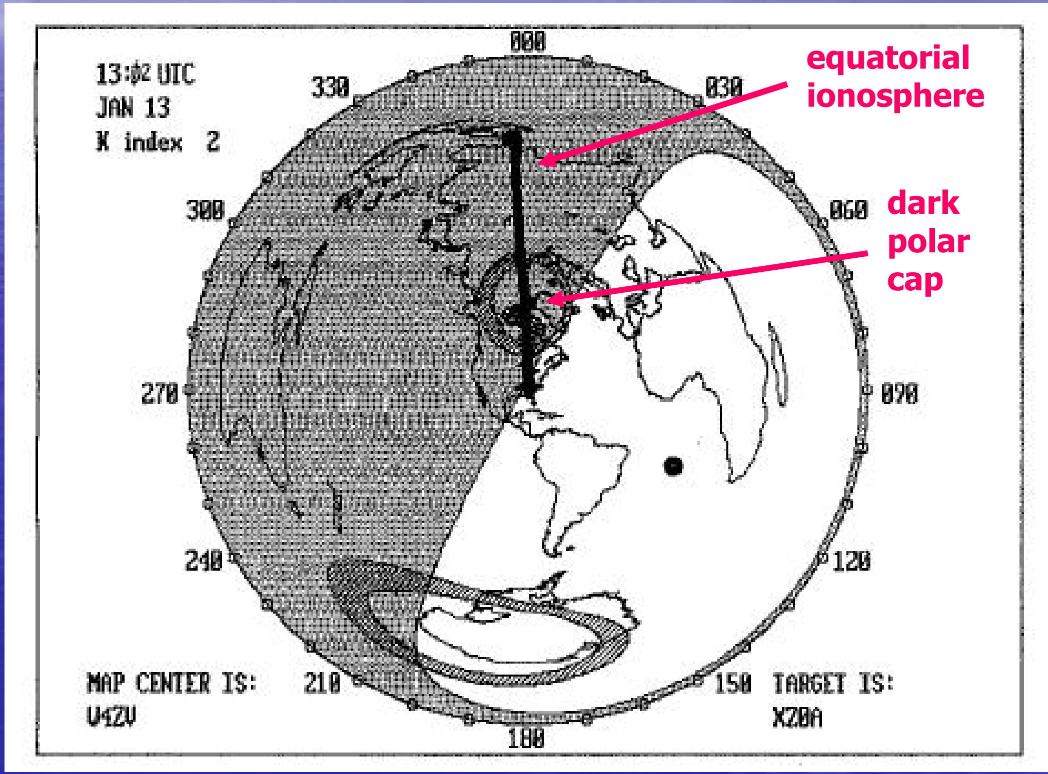
diurnal pattern

seasonal pattern

- SSSP (Summer Solstice Short- path Propagation) coined by JE1BMJ, et al.
- Hypothesis is PMSE for 6m QSOs that go through the high latitudes
  - JA to W4, for example

Drifting F_2 Patches

- Limited region of increased plasma density with a horizontal dimension on the order of 100-1000 km
- Ionization of a patch is significantly higher than the background F2 region ionization – up to 10 times higher
- The average duration is around one hour
- Occur mostly in the winter months
- Occur in the daytime hours
- Occur throughout an entire solar cycle with solar maximum having the most occurrences
- Occur most often when the interplanetary magnetic field turns southward.



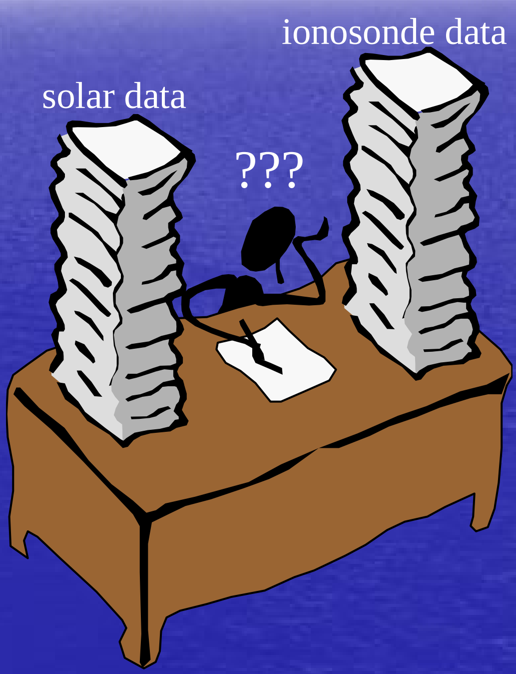
W4ZV to XZ0A in January 13, 2000 on 10m at 1302 UTC

Session 2B

Propagation Predictions

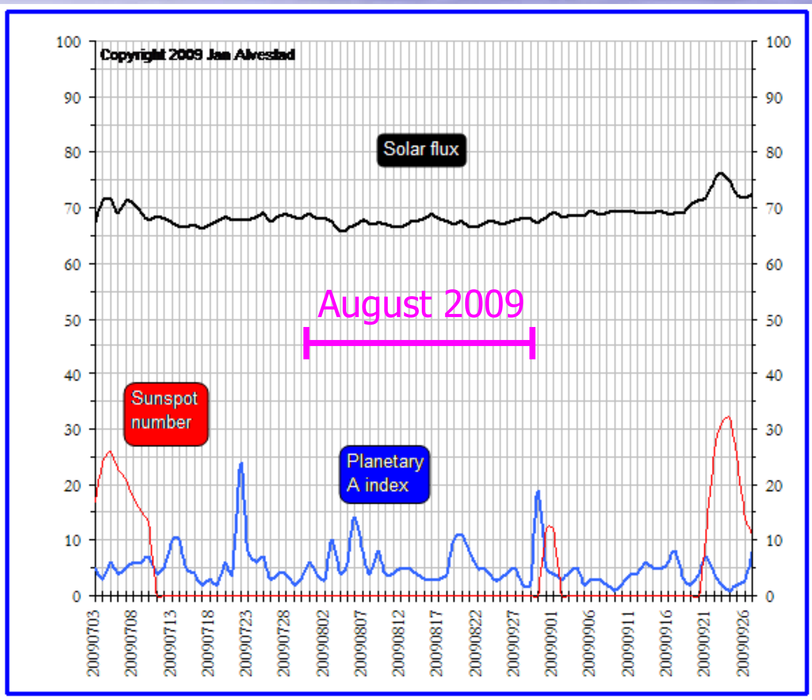
Solar Data and Ionosphere Data

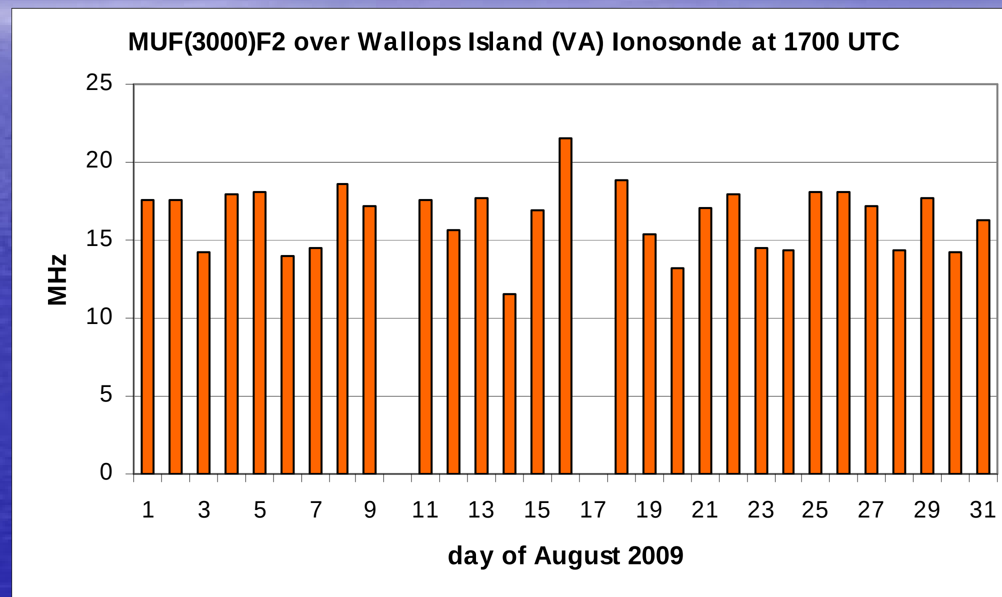
- Many years of solar data and worldwide ionosonde data collected
- The task of the propagation prediction developers was to determine the correlation between solar data and ionosonde data
- It would have been nice to find a correlation between what the ionosphere was doing on a given day and what the Sun was doing on the same day



But That Didn’t Happen

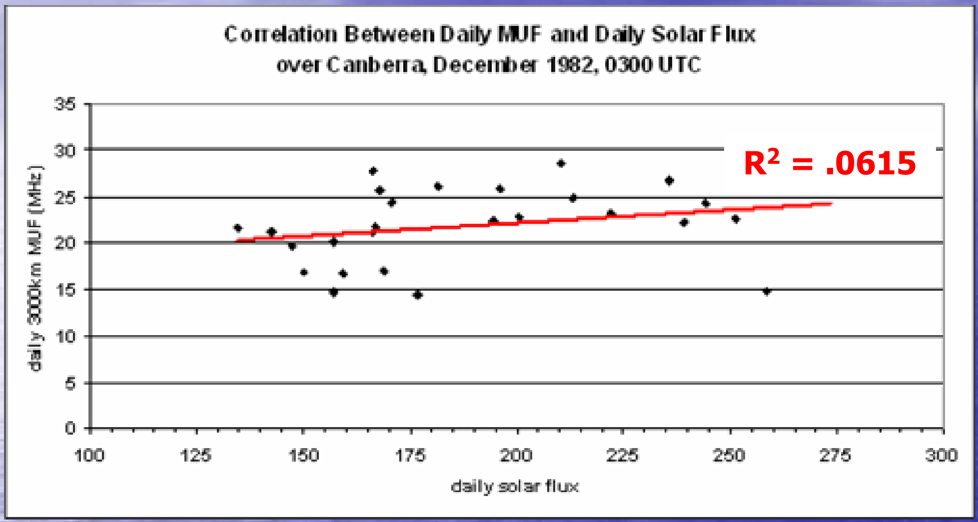
http://www.solen.info/solar/





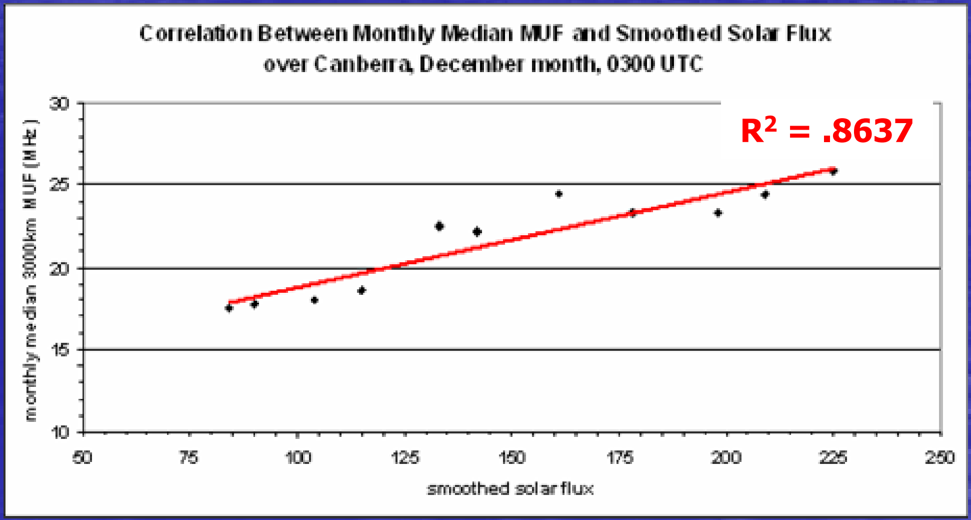
- August 2009
  - Zero sunspots
  - Constant 10.7 cm flux
- No correlation between daily values
  - Low of 11.6 MHz on August 14
  - High of 21.5 MHz on August 16
- Indicates there are other factors in determining the ultimate ionization

So Now What?



Not too good - the developers were forced to come up with a statistical model over a month's time frame

Good – smoothed solar flux (or smoothed sunspot number) and monthly median parameters



How Do You Determine the Monthly Median?

raw data

day	foF2
1	5.4
2	4.3
3	4.8
4	4.6
5	4.7
6	4.6
7	4.8
8	4.4
9	4.4
10	0
11	4.2
12	4.9
13	4.2
14	4.6
15	4.5
16	4.9
17	0
18	4.4
19	5.2
20	4.8
21	4.9
22	4.9
23	4.8
24	4.7
25	4.4
26	4.4
27	4.3
28	4.8
29	4.9
30	4.9
31	4.6

put foF_2 in ascending order

median implies 50%

day	foF2
11	4.2
13	4.2
2	4.3
27	4.3
8	4.4
9	4.4
18	4.4
25	4.4
26	4.4
15	4.5
4	4.6
6	4.6
14	4.6
31	4.6
5	4.7
24	4.7
3	4.8
7	4.8
20	4.8
23	4.8
28	4.8
12	4.9
16	4.9
21	4.9
22	4.9
29	4.9
30	4.9
19	5.2
1	5.4

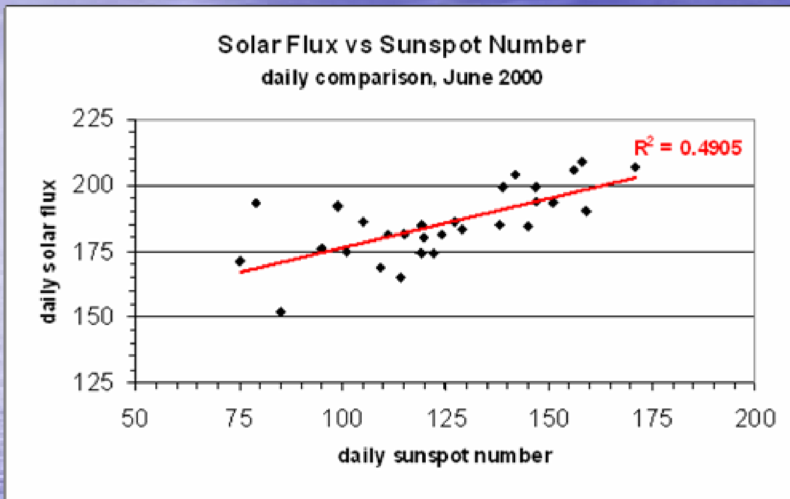
half of the values below median

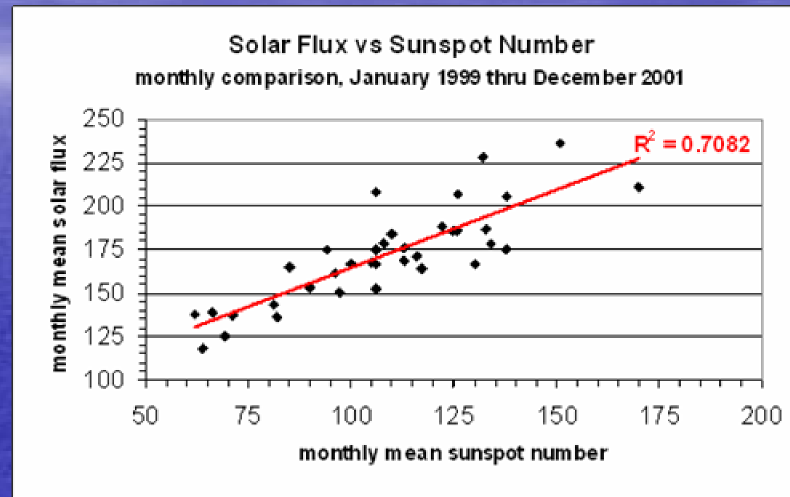
median

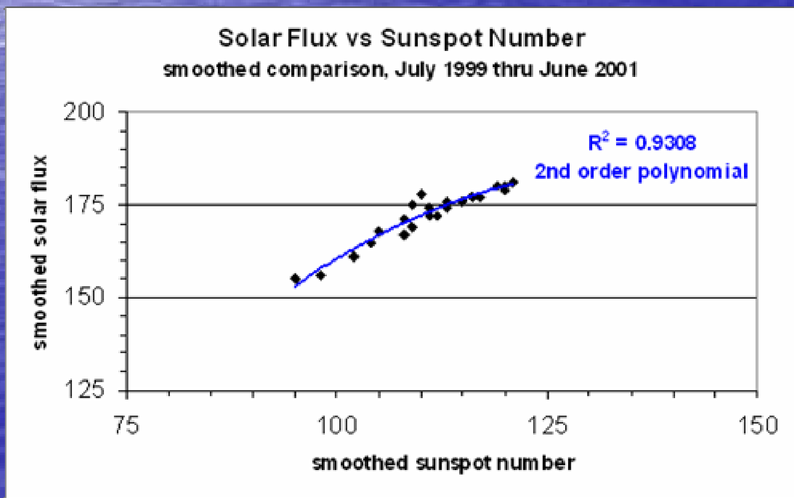
half of the values above median

Variation about the median follows a Chi-squared distribution, thus probabilities can be calculated (more on this later)

Correlation Between SF and SSN







Smoothed solar flux

$$\varphi_{12} = 63.75 + 0.728\, R_{12} + 0.00089\, (R_{12})^2$$

Smoothed sunspot number

$$R_{12} = (93918.4 + 1117.3\, \varphi_{12})^{1/2} - 406.37$$

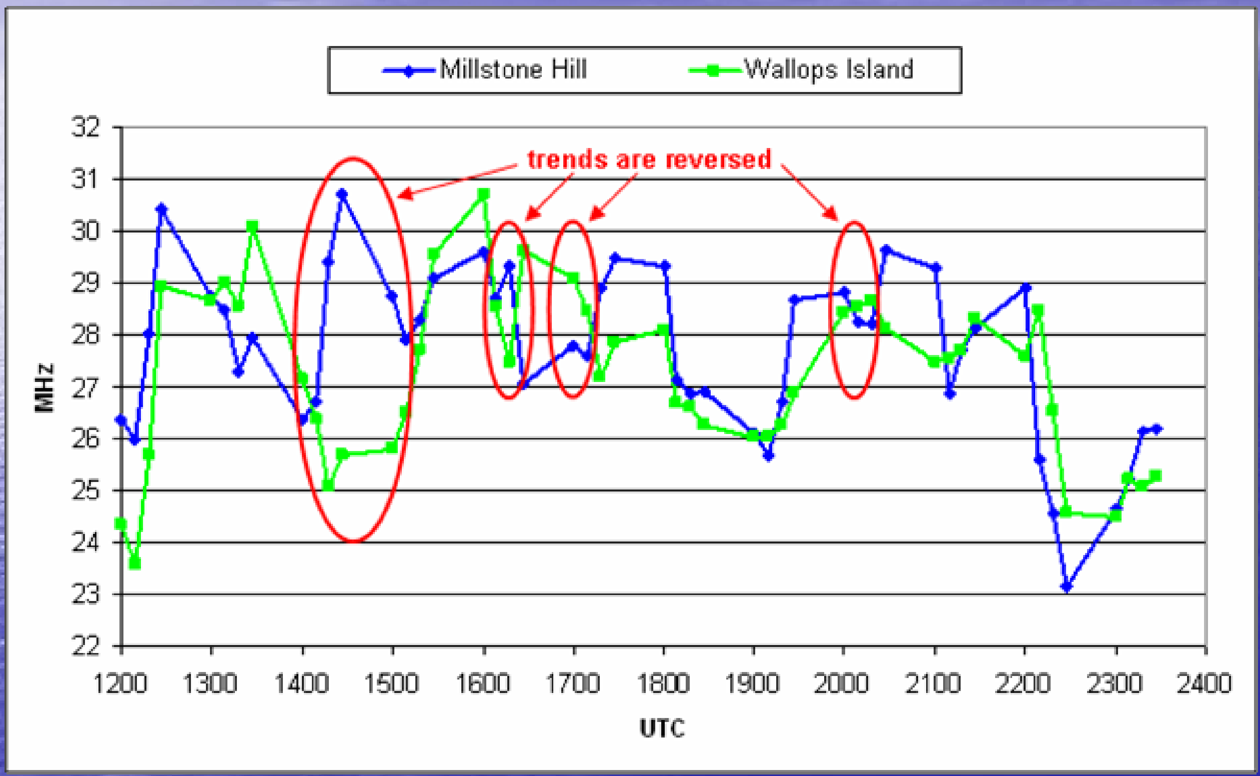
Using these equations to convert between <u>daily</u> solar flux and <u>daily</u> sunspot number results in a lot of uncertainty

What Causes Variability?

Solar ionizing radiation	Solar wind/geomagnetic activity/electrodynamics	Neutral atmosphere
Solar flares	Day-to-day 'low level' variability	Solar and lunar tides
Solar rotation (27 day) variations	Substorms	Acoustic and gravity waves
Formation and decay of active regions	Magnetic storms	Planetary waves
Seasonal variation of Sun's declination	IMF/Solar wind sector structure	Quasi-biennial oscillation
Annual variation of Sun-Earth distance	Energetic particle precipitation	Lower atmosphere coupling
Solar cycle variation (11 and 22 yrs)	Fountain effect at low latitudes	Surface phenomena (earthquakes)
Longer period solar epochs	Magnetospheric electric fields	Surface phenomena (volcanoes)
	Plasma convection at high latitudes	
	Field-aligned plasma flows	
	Electric fields from lightning	

- Rishbeth and Mendillo, Journal of Atmospheric and Solar-Terrestrial Physics, Vol 63, 2001, pp 1661-1680
  - Looked at 34 years of foF_2 data
  - Used data from 13 ionosondes
  - Day-to-day daytime variability (std dev/monthly mean) = 20%
    - Solar ionizing radiation contributed about 3%
    - Solar wind, geomagnetic field activity, electrodynamics about 13%
    - Neutral atmosphere about 15%
    - $[20\%]^2 = [3\%]^2 + [13\%]^2 + [15\%]^2$

Is the Ionosphere In Step?



- 3000 km MUF over Millstone Hill and Wallops Island
- Separated by 653 km = 408 miles
- Several periods highlighted that show ionosphere was going opposite ways
- Worldwide ionosphere not necessarily in step

K9LA to ZF

- Latitudes / longitudes
  - K9LA = 41.0N / 85.0W
  - ZF = 19.5N / 80.5W
- October 2004
  - Smoothed sunspot number ~ 35 (smoothed solar flux ~ 91)
- Antennas
  - Small Yagis on both ends = 12 dBi gain
- Power
  - 1000 Watts on both ends
- Bands and Path
  - 20m, 17m, 15m on the Short Path
- We'll use VOACAP
  - When you download VOACAP (comes with ICEPAC and REC533), read the Technical Manual and User's Manual – lots of good info

VOACAP Input Parameters

- Method
  - Controls the type of program analysis and the predictions performed
  - Recommend using Method 30 (Short\Long Smoothing) most of the time
  - Methods 1 and 25 helpful for analysis of the ionosphere
- Coefficients
  - CCIR (International Radio Consultative Committee)
    - Shortcomings over oceans and in southern hemisphere
    - Most validated
  - URSI (International Union of Radio Scientists)
    - Rush, et al, used aeronomic theory to fill in the gaps
- Groups
  - Month.Day
    - 10.00 means centered on the middle of October
    - 10.05 means centered on the 5th of October
      - Defaults to URSI coefficients

VOACAP Input Parameters

- System
  - Noise — default is residential
  - Min Angle — 1 degree (emulate obstructions to radiation)
  - Req Rel — default is 90%
  - Req SNR — 48 dB in 1 Hz (13 dB in 3 KHz: 90% intelligibility)
  - Multi Tol — default is 3 dB
  - Multi Del — default is .1 milliseconds
- Fprob
  - Multipliers to increase or reduce MUF
    - Default is 1.00 for foE, foF1, foF2 and 0.00 for foEs

For more details on setting up and running VOACAP, either visit http://lipas.uwasa.fi/~jpe/voacap/ by Jari OH6BG (lots of good info) or visit the Tutorials link at http://k9la.us

Prediction Printout

13.0	20.9	14.1	18.1	21.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	FREQ
	1F2	1F2	1F2	1F2	-	-	-	-	-	-	-	-	MODE
	10.0	4.7	5.5	10.0	-	-	-	-	-	-	-	-	TANGLE
	8.6	8.4	8.4	8.6	-	-	-	-	-	-	-	-	DELAY
	347	222	240	347	-	-	-	-	-	-	-	-	V HITE
	0.50	0.99	0.83	0.46	-	-	-	-	-	-	-	-	MUFday
	123	112	113	124	-	-	-	-	-	-	-	-	LOSS
	28	36	37	27	-	-	-	-	-	-	-	-	DBU
	-93	-82	-83	-94	-	-	-	-	-	-	-	-	S DBW
	-168	-163	-166	-168	-	-	-	-	-	-	-	-	N DBW
	75	80	83	74	-	-	-	-	-	-	-	-	SNR
	-27	-32	-35	-26	-	-	-	-	-	-	-	-	RPWRG
	0.90	1.00	1.00	0.89	-	-	-	-	-	-	-	-	REL
	0.00	0.00	0.00	0.00	-	-	-	-	-	-	-	-	MPROB
	1.00	1.00	1.00	1.00	-	-	-	-	-	-	-	-	S PRB
	25.0	8.4	12.5	25.0	-	-	-	-	-	-	-	-	SIG LW
	13.1	4.9	5.3	14.0	-	-	-	-	-	-	-	-	SIG UP
	26.8	12.6	15.7	26.8	-	-	-	-	-	-	-	-	SNR LW
	14.3	7.2	7.8	15.2	-	-	-	-	-	-	-	-	SNR UP
	12.0	12.0	12.0	12.0	-	-	-	-	-	-	-	-	TGAIN
	12.0	12.0	12.0	12.0	-	-	-	-	-	-	-	-	RGAIN
	75	80	83	74	-	-	-	-	-	-	-	-	SNRxx

Focus on 15m at 1300 UTC

time

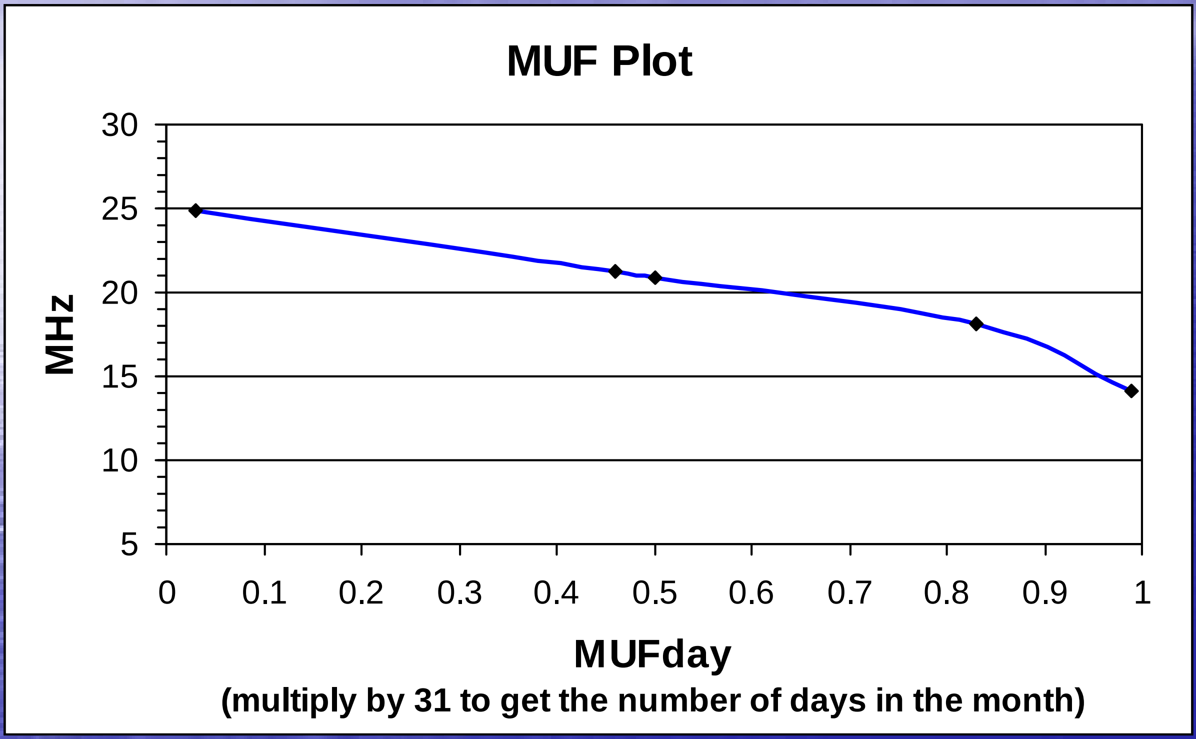
monthly median MUF

MUFday for 15m

signal power

13.0	20.9	14.1	18.1	21.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	FREQ
	1F2	1F2	1F2	1F2	-	-	-	-	-	-	-	-	MODE
	10.0	4.7	5.5	10.0	-	-	-	-	-	-	-	-	TANGLE
	8.6	8.4	8.4	8.6	-	-	-	-	-	-	-	-	DELAY
	347	222	240	347	-	-	-	-	-	-	-	-	V HITE
	0.50	0.99	0.83	0.46	-	-	-	-	-	-	-	-	MUFday
	123	112	113	124	-	-	-	-	-	-	-	-	LOSS
	28	36	37	27	-	-	-	-	-	-	-	-	DBU
	-93	-82	-83	-94	-	-	-	-	-	-	-	-	S DBW
	-168	-163	-166	-168	-	-	-	-	-	-	-	-	N DBW
	75	80	83	74	-	-	-	-	-	-	-	-	SNR
	-27	-32	-35	-26	-	-	-	-	-	-	-	-	RPWRG
	0.90	1.00	1.00	0.89	-	-	-	-	-	-	-	-	REL
	0.00	0.00	0.00	0.00	-	-	-	-	-	-	-	-	MPROB
	1.00	1.00	1.00	1.00	-	-	-	-	-	-	-	-	S PRB
	25.0	8.4	12.5	25.0	-	-	-	-	-	-	-	-	SIG LW
	13.1	4.9	5.3	14.0	-	-	-	-	-	-	-	-	SIG UP
	26.8	12.6	15.7	26.8	-	-	-	-	-	-	-	-	SNR LW
	14.3	7.2	7.8	15.2	-	-	-	-	-	-	-	-	SNR UP
	12.0	12.0	12.0	12.0	-	-	-	-	-	-	-	-	TGAIN
	12.0	12.0	12.0	12.0	-	-	-	-	-	-	-	-	RGAIN
	75	80	83	74	-	-	-	-	-	-	-	-	SNRxx

15m Openings at 1300 UTC



- 20.9 MHz (monthly median)
  - Enough ionization on half the days of the month
- 21.2 MHz
  - Enough ionization on .46 x 31 = 14 days of the month
- 14 MHz and below
  - Enough ionization every day of the month
- 24.9 MHz
  - Enough ionization on 1 day of the month
- 28.3 MHz
  - Not enough ionization on any day

We can't predict which days are the "good" days

15m Signal Power

- -94 dBW (monthly median) = -64 dBm
- Assume
  - S9 = -73 dBm (50 microvolts into 50Ω)
  - one S-unit = 5 dB
    - typical of receivers I've measured
      - except below S3 or so it's only a couple dB per S-unit
- -64 dBm = 10 dB over S9
- Variability about the monthly median from ionospheric texts (for example, Supplement to Report 252-2, CCIR, 1978)
- Signal power could be from one S-unit higher to two S-units lower on any given day on this path
  - S9 to 15 over 9 for this path
- Rule of thumb – actual signal power for any path could be from a couple S-units higher to several S-units lower than median on any given day

S9+10	**-63 dBm**
S9	**-73 dBm**
S8	**-78 dBm**
S7	**-83 dBm**
S6	**-88 dBm**
S5	**-93 dBm**
S4	**-98 dBm**
S3	**-103 dBm**
S2	**-108 dBm**
S1	**-113 dBm**

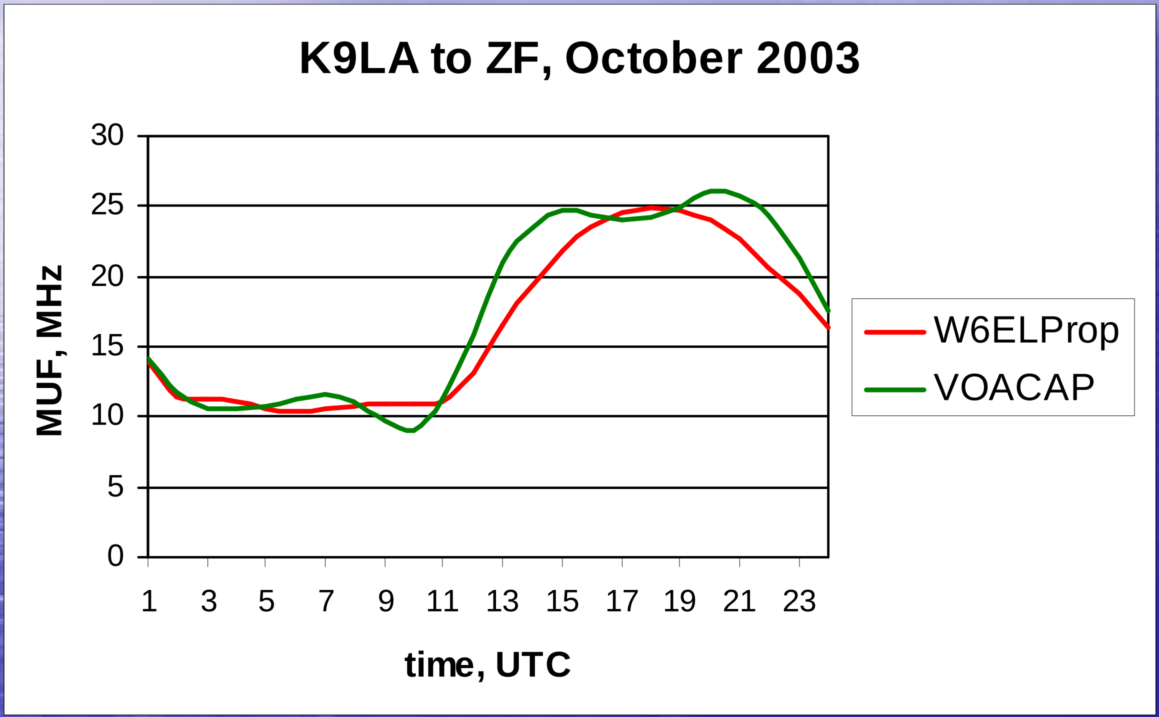
Don't make assumptions about your S-meter – measure it

What's Different with W6ELProp?

- Underlying concept is still the correlation between a smoothed solar parameter and monthly median ionospheric parameters
- For foF_2, W6ELProp uses equations developed by Raymond Fricker of the BBC
  - VOACAP uses database of numerical coefficients to describe worldwide ionosphere
  - Another option is IRI (PropLab Pro)
- W6ELProp rigorously calculates signal strength using CCIR methods
  - VOACAP calibrated against actual measurements

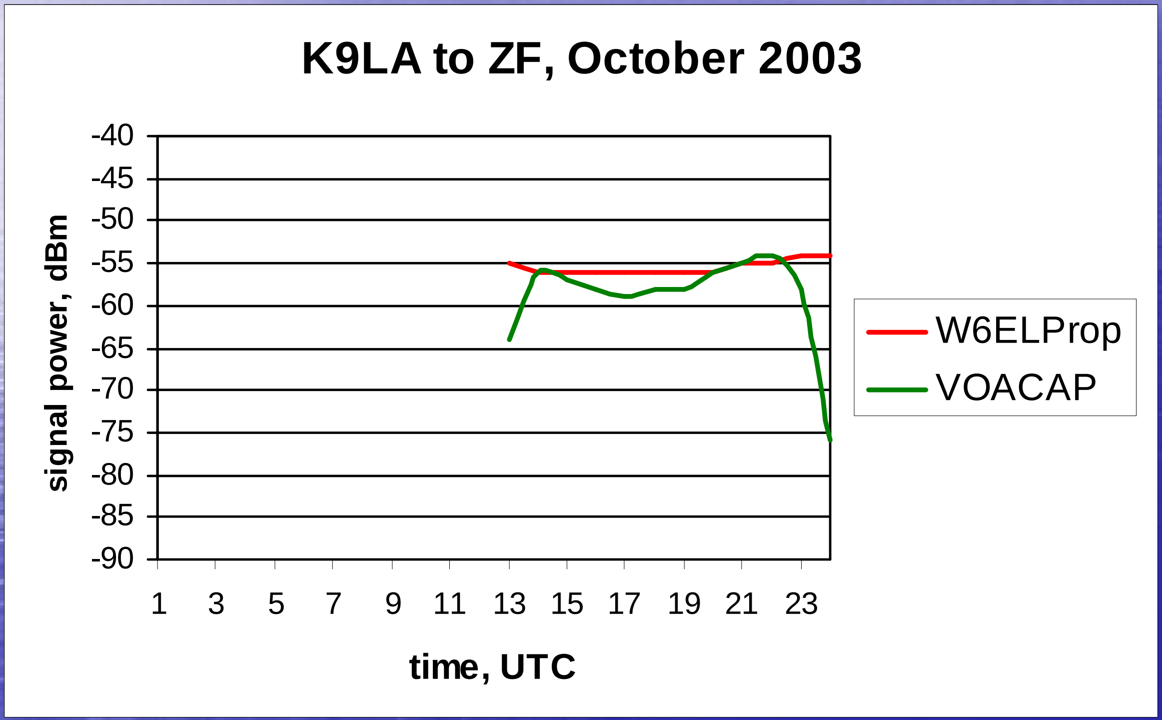
For more details on setting up and running W6ELProp, visit the Tutorials link at http://k9la.us

Comparison - MUF



- Close, but there are differences – especially around sunrise and sunset
- The difference is how the F_2 region is represented in the model
  - VOACAP is database of numerical coefficients
  - Fricker's equations in W6ELProp 'simplified' this to 23 equations (1 main function + 22 modifying functions)

Comparison – Signal Strength

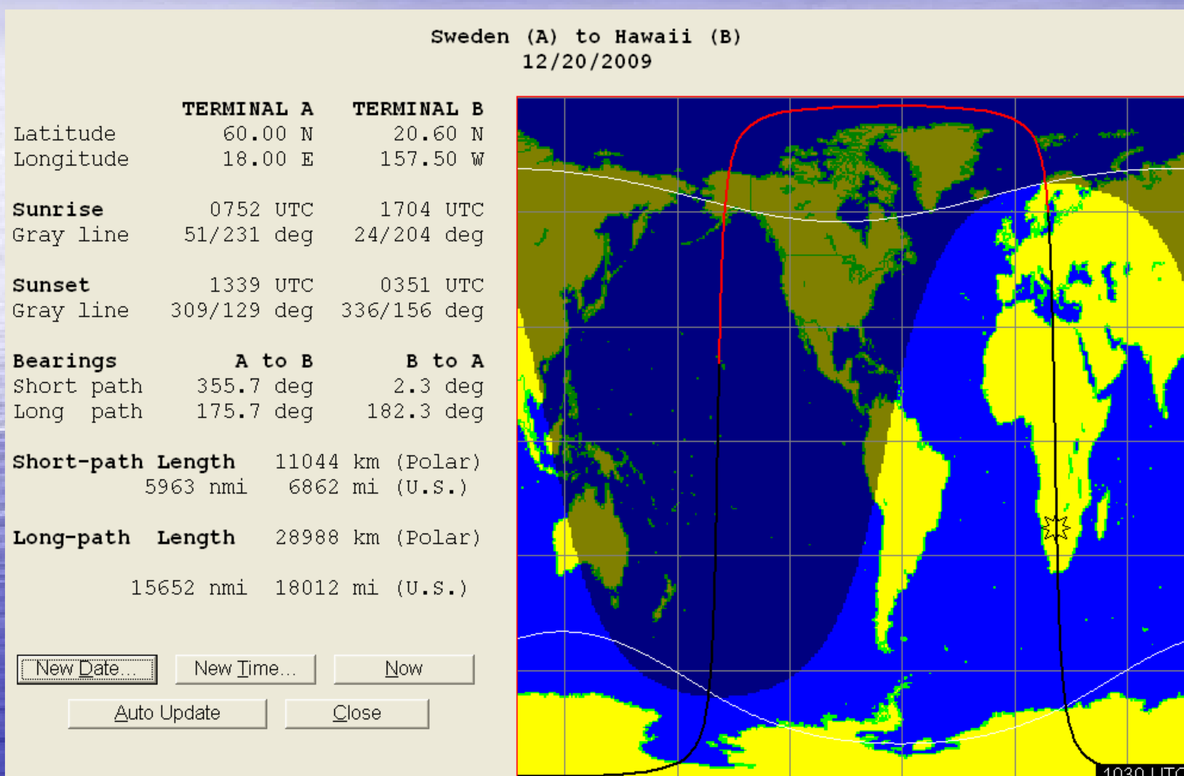


- In general W6ELProp predicts higher signal strengths
- VOACAP is more realistic with respect to signal strength

The Mapping Feature in W6ELProp

- This is a great tool for low band operating
- Recently on the topband reflector SM2EKM told of a 160m QSO with KH6AT in late December at local noon
- Without digging any farther, this sounds like a very unusual QSO

SM to KH6 in Dec at SM Noon



- Path on SM end is perpendicular to the terminator
  - RF from SM encounters the D region right around the terminator
  - But the solar zenith angle is high
- Rest of path is in darkness
- A index and K index are important for this over-the-pole path
  - Were at zero for a couple days

Summary of Predictions

- We don't have daily predictions
- Predictions are statistical over a month's time frame
- All prediction software is based on the correlation between a smoothed solar index and monthly median ionospheric parameters
- Many good programs out there with different presentation formats and different bells and whistles
- Don't forget the predictions offered by Dean N6BV
  - VOACAP predictions to/from more than 240 locations
  - 160m – 10m, six phases of solar cycle, each month
  - Available on a CD from Radioware & Radio Bookstore
- Choose the one you like the best
  - VOACAP considered the standard
  - Several use the VOACAP engine
- Interested in validating a prediction?
  - Visit the Basic Concepts link at http://k9la.us

Session 3A
Disturbances to Propagation

The NOAA Categories

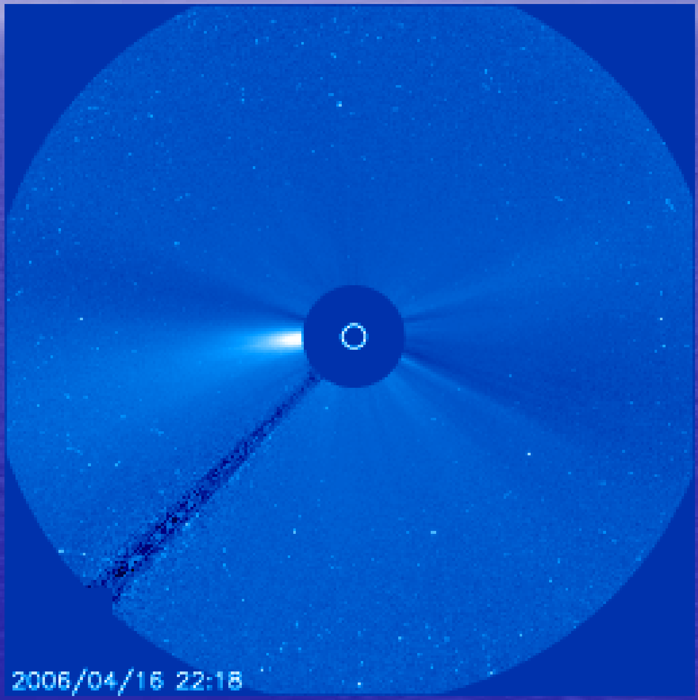
- Geomagnetic storms (G)
  - K and A index
- Solar radiation storms (S)
  - Energetic protons into the polar cap
- Radio blackouts (R)
  - Electromagnetic radiation from .1 to 1 nanometer

http://www.swpc.noaa.gov/NOAAscales/

Geomagnetic Storm

- Caused by an Earth-directed Coronal Mass Ejection (CME) or a high-speed wind stream from a coronal hole
  - Solar wind can be up to 2000km/sec
- Can result in
  - Decreased F region ionization at mid and high latitudes
    - Lower MUF (Maximum Usable Frequency)
  - Increased E region ionization at high latitudes
    - Auroral displays
    - Auroral-E
      - Increased absorption
      - Skewed paths
  - Increased F region ionization at low latitudes
- Most geomagnetic storms occur at peak (CMEs) and during the declining phase (CH) of a sunspot cycle

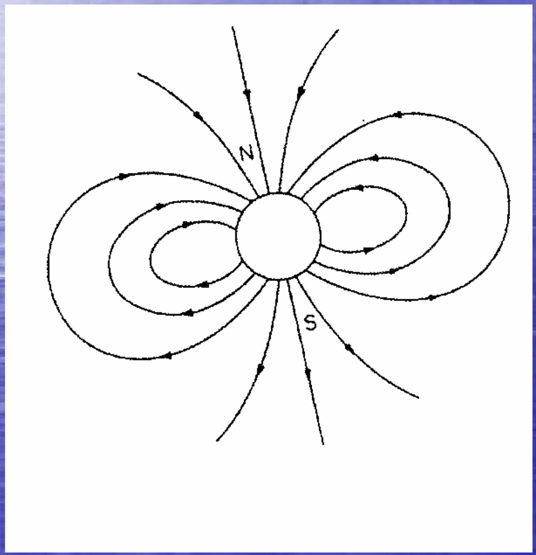
CME



Coronagraph (telescope with an appropriately-sized occulting disk at the focal point)

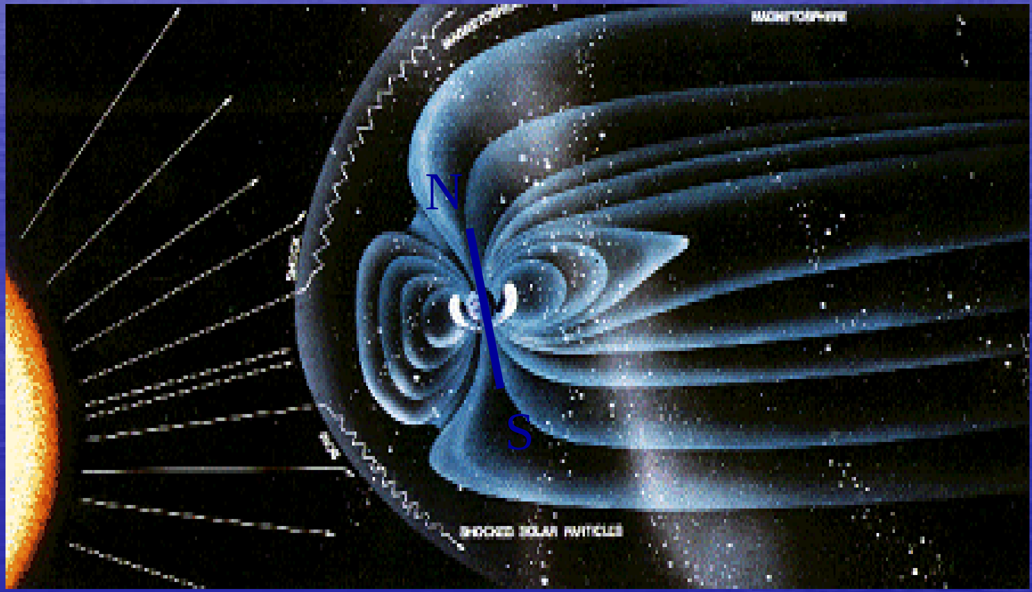
The Earth-Sun Relationship

The Earth's magnetic field ***without*** the influence of the Sun



pretty much the classic textbook bar magnet

The Earth's magnetic field ***with*** the influence of the Sun

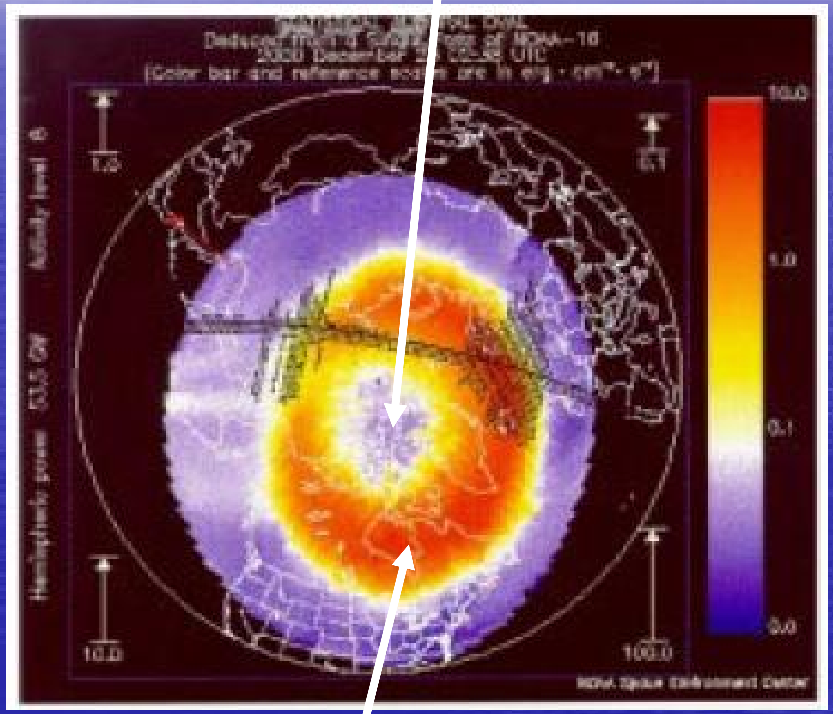


Shock wave from CME or high-speed solar wind distorts the Earth's magnetic field

Solar Radiation Storm

- Caused by very energetic protons emitted by a large solar flare
- Can result in increased absorption at D region altitudes in the polar cap
  - Directed to the polar cap by the Earth's magnetic field
  - Polar cap is circular area inside the auroral oval
  - Degrades over-the-pole paths
- Most solar radiation storms occur around the peak of a sunspot cycle

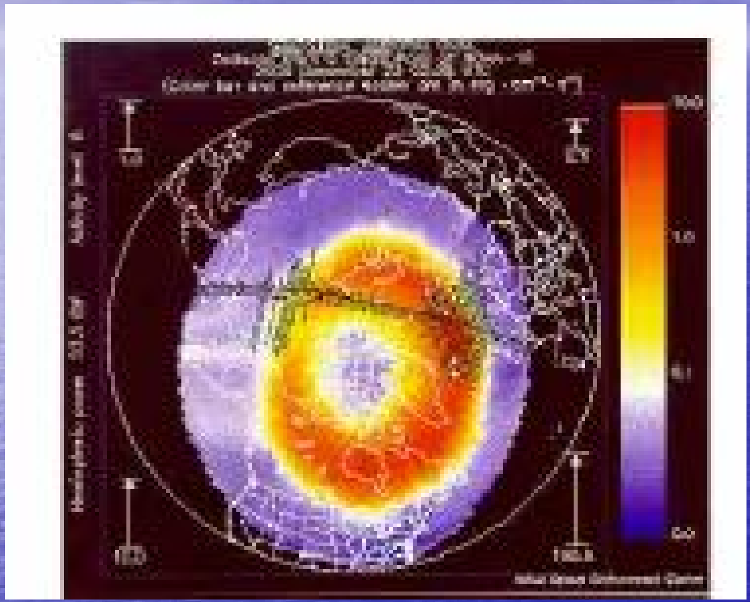
polar cap



auroral oval

(1 of 10 canned maps that shows statistically where visual aurora can occur)

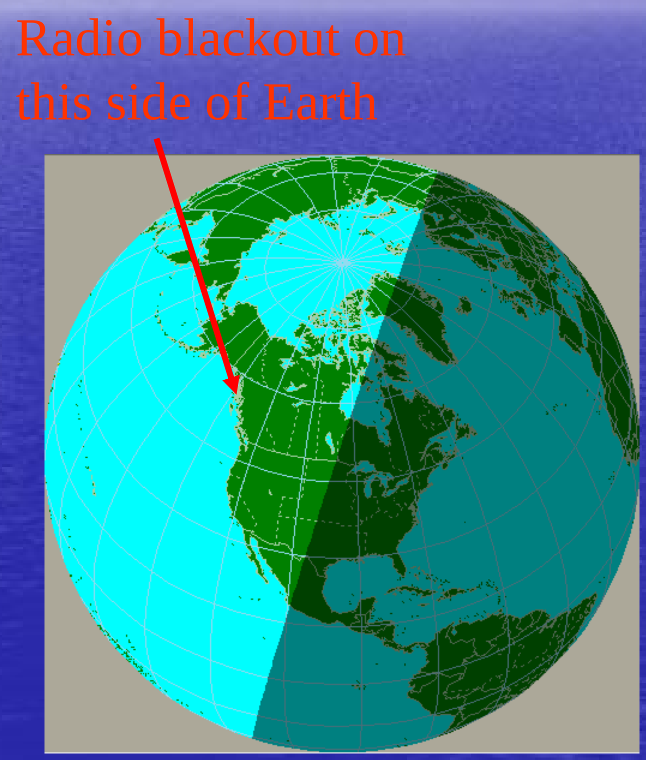
PMAPs vs Reality



PMAP and visual image for the same day at the same time

Radio Blackout

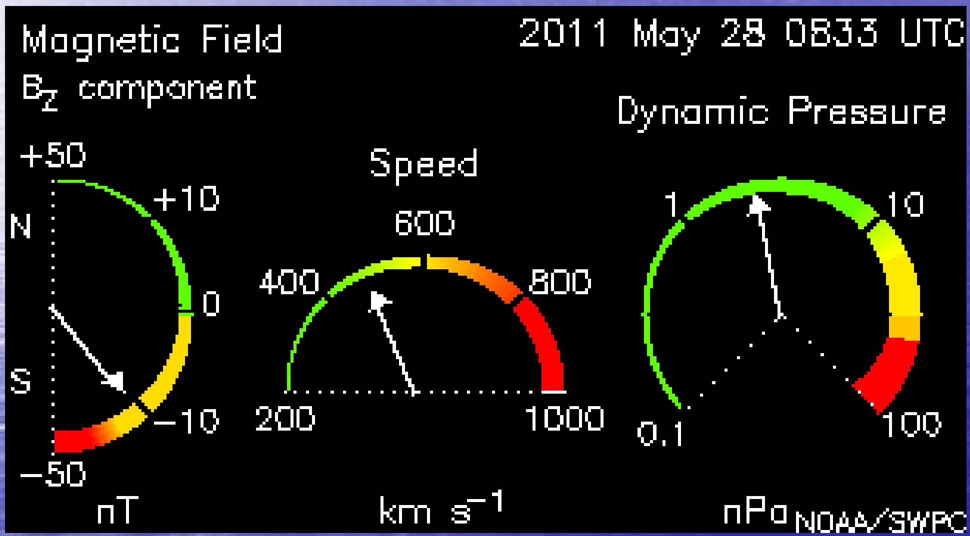
- Caused by radiation at short x-ray wavelengths from large solar flares
- Can result in a blackout on the sunlit side of the Earth due to increased D region absorption
  - Most pronounced at low frequencies
- Most radio blackouts occur around the peak of a sunspot cycle



Session 3B

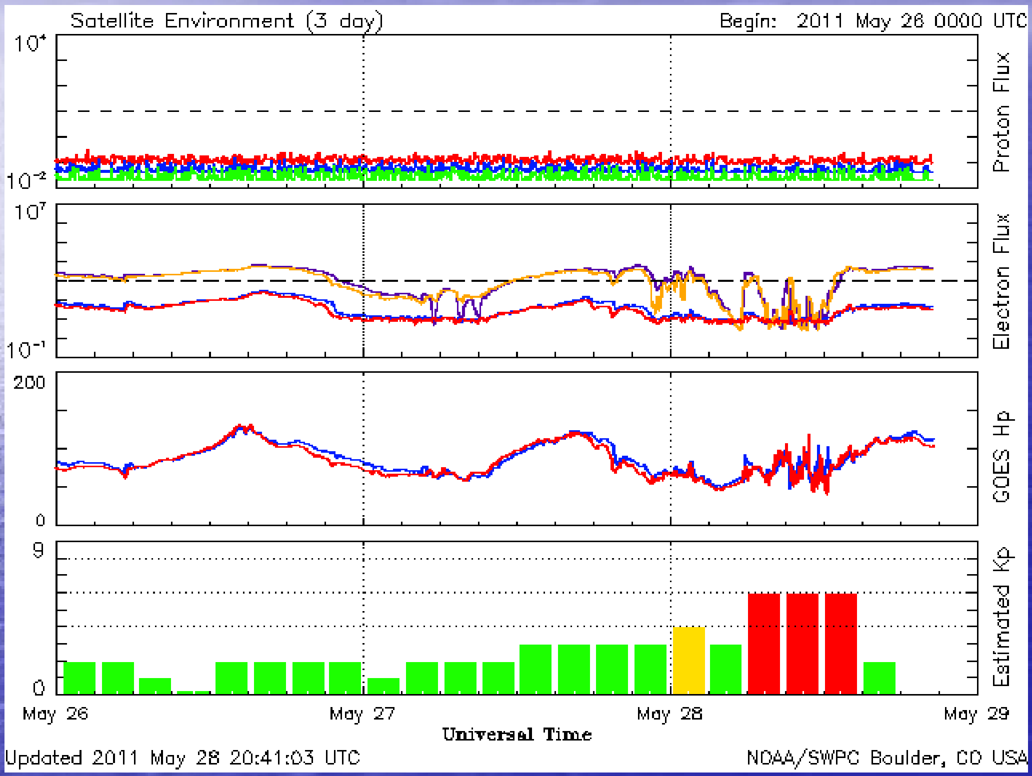
Interpreting Space Weather

The Dials At SWPC



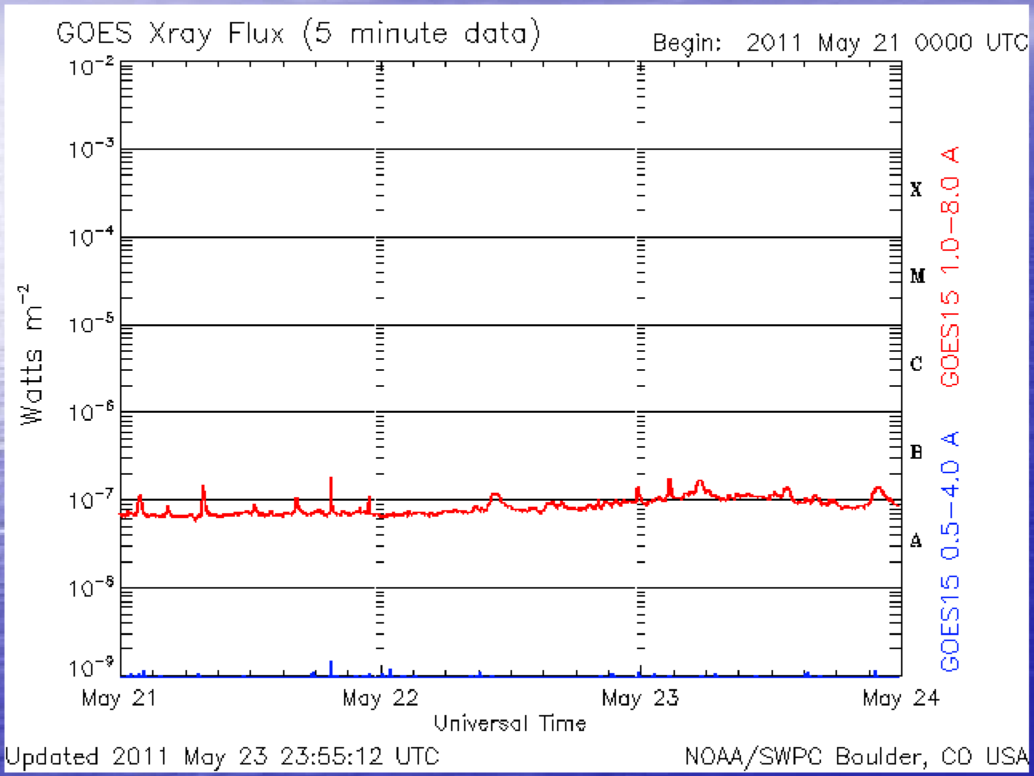
- Pay attention to the colors
  - Green – good
  - Yellow – caution
  - Red – not good
    - Southward interplanetary magnetic field connects with the Earth's magnetic field
- Average solar wind speed is 400 km/sec
- P = 1.6726e-6 * n * V^2
  where Pressure P is in nPa (nano Pascals), n is the density in particles cm-3 and V is the speed in km s-1 of the solar wind.

Other Data at SWPC



- Proton flux
  - Watch for spike
  - From big solar flares
  - Causes absorption in polar cap
- Electron flux
  - At geosynchronous altitudes
  - When it dips, watch for auroral activity
- GOES Hp
  - Component that is parallel to Earth's rotational axis
  - Watch when it dips
- Estimated Kp
  - Green (quiet), yellow (active), red (disturbed)

More Data at SWPC



- GOES15 1.0-8.0 A
  - 0.1 – 0.8 nm
  - Ionizes the D region
- GOES15 0.5-4.0A
  - 0.05 – 0.4 nm
  - Ionizes the D region and the lower E region
- At solar max, high background values
- At solar min, low background values
- Watch for spikes to M and X levels
  - Absorption on daylight side of Earth
  - Concurrent CME?

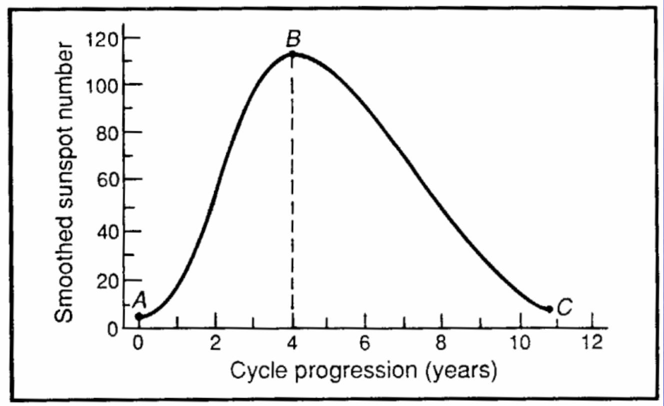
General SF, A, and K

- K index is 3-hour value
  - Logarithmic scale
  - 0 to 9
- A index is daily average of the 8 K indices
  - Linear index
  - 0 to 400
  - Have to convert the K indices to a indices to mathematically average
- Lower HF bands
  - Generally want low 10.7 cm solar flux, low A, and low K
- Higher HF bands
  - Generally want high 10.7 cm solar flux, low A, and low K
- VHF
  - For auroral propagation, generally want high A and high K

Session 3C
Solar Cycles

Solar Cycles

- European astronomers began keeping sunspot records on a regular basis in the middle of the 18th century
- Hendrick Schwabe began counting sunspots in the 1820s
  - Credited with the discovery of solar cycles
  - Published his findings in 1843



"average" solar cycle

- Rudolph Wolf devised a standard method to count sunspots

- R = k (10g + s)
  - Wolf's relative sunspot number
  - Gives greater weight to large sunspot groups
- In 1852 Wolf converted data back to 1749 to his sunspot number

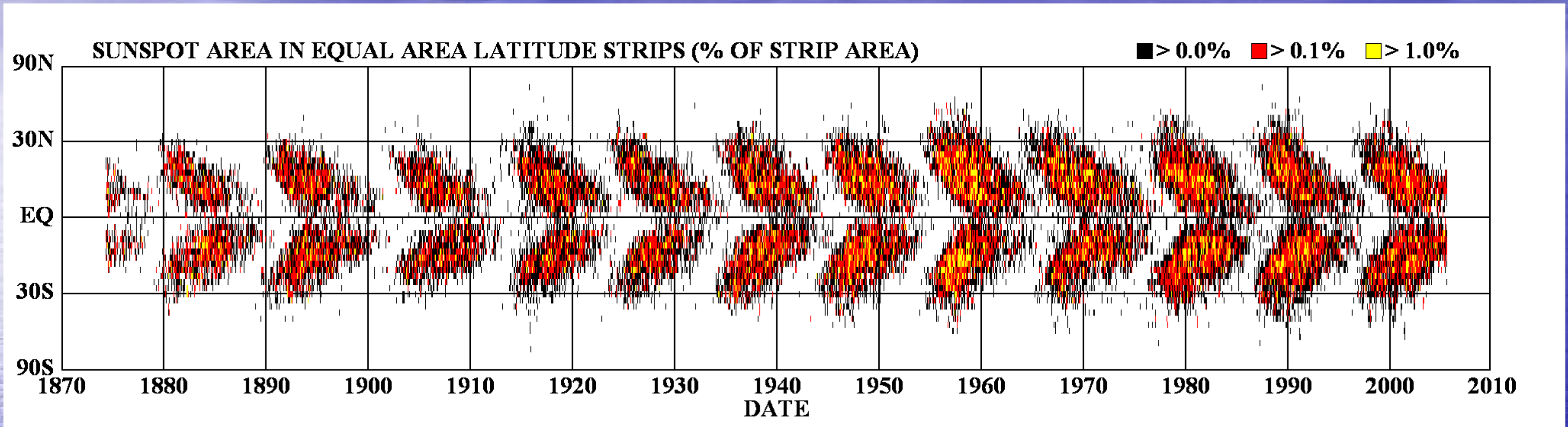
Measuring a Solar Cycle

- Plot of daily sunspot number is very spiky
- Plot of monthly mean sunspot number still spiky
- Official measurement of a solar cycle uses the smoothed sunspot number R_{12}
  - Calculated from monthly means

R_{12} for August 2008 = .5 x Feb08 + Mar08 + Apr08 + May08 + Jun08 + Jul08 +
Aug08 + Sep08 + Oct08 + Nov08 + Dec08 + Jan09 + .5 x Feb09

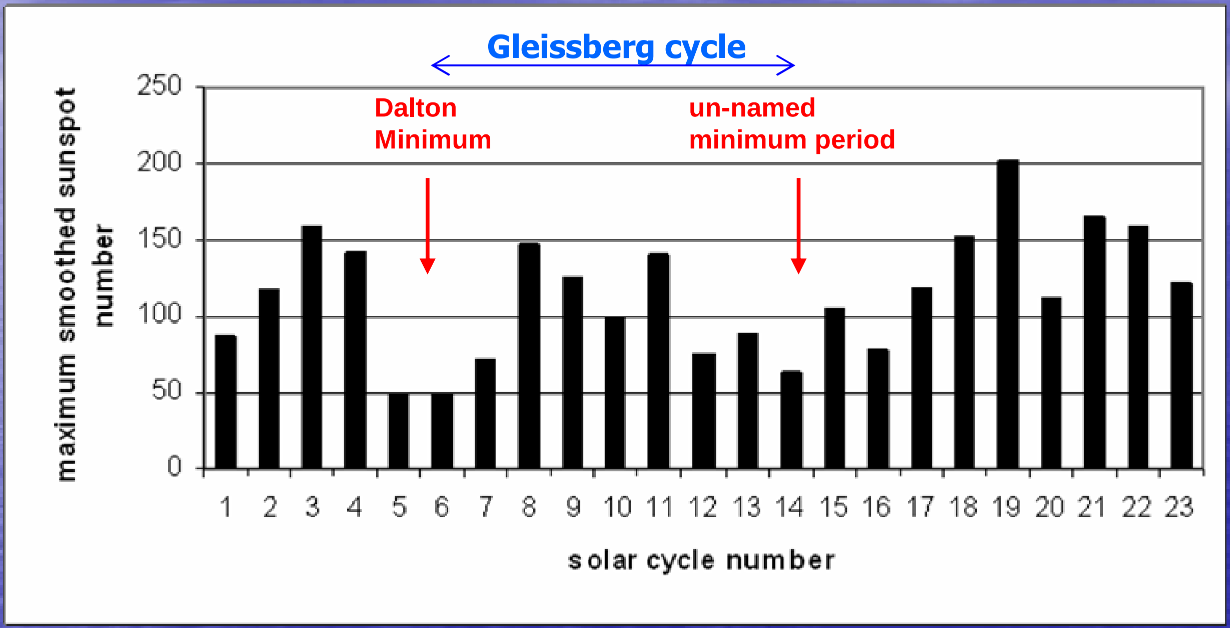
thus the official smoothed sunspot number is 6 months behind the current month
latest R_{12} as of May 2011 is for October 10

When Does A New Cycle Start?



- Butterfly diagram
- Sunspots of new cycle are at higher latitudes
  - Sunspots of old cycle are at lower latitudes
- Sunspots of new cycle are of opposite polarity compared to sunspots of old cycle
  - And the sunspots in the northern and southern hemisphere are of opposite polarity
- Can have asymmetry between the two hemispheres

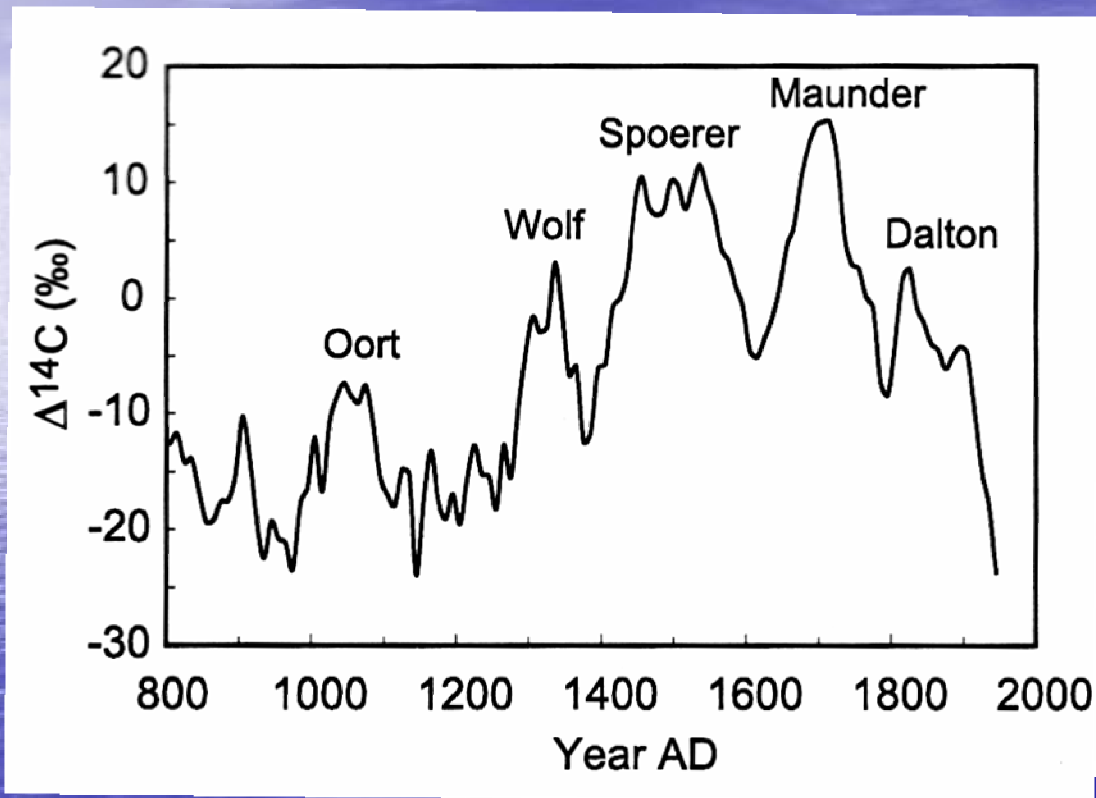
Historical Records



Cycle 1 started in 1755
Recorded history is cyclic in nature
3 maximum periods and 2 minimum periods
- **Cycles 5, 6, and 7 are called Dalton minimum**

Looks like we're headed for another minimum period

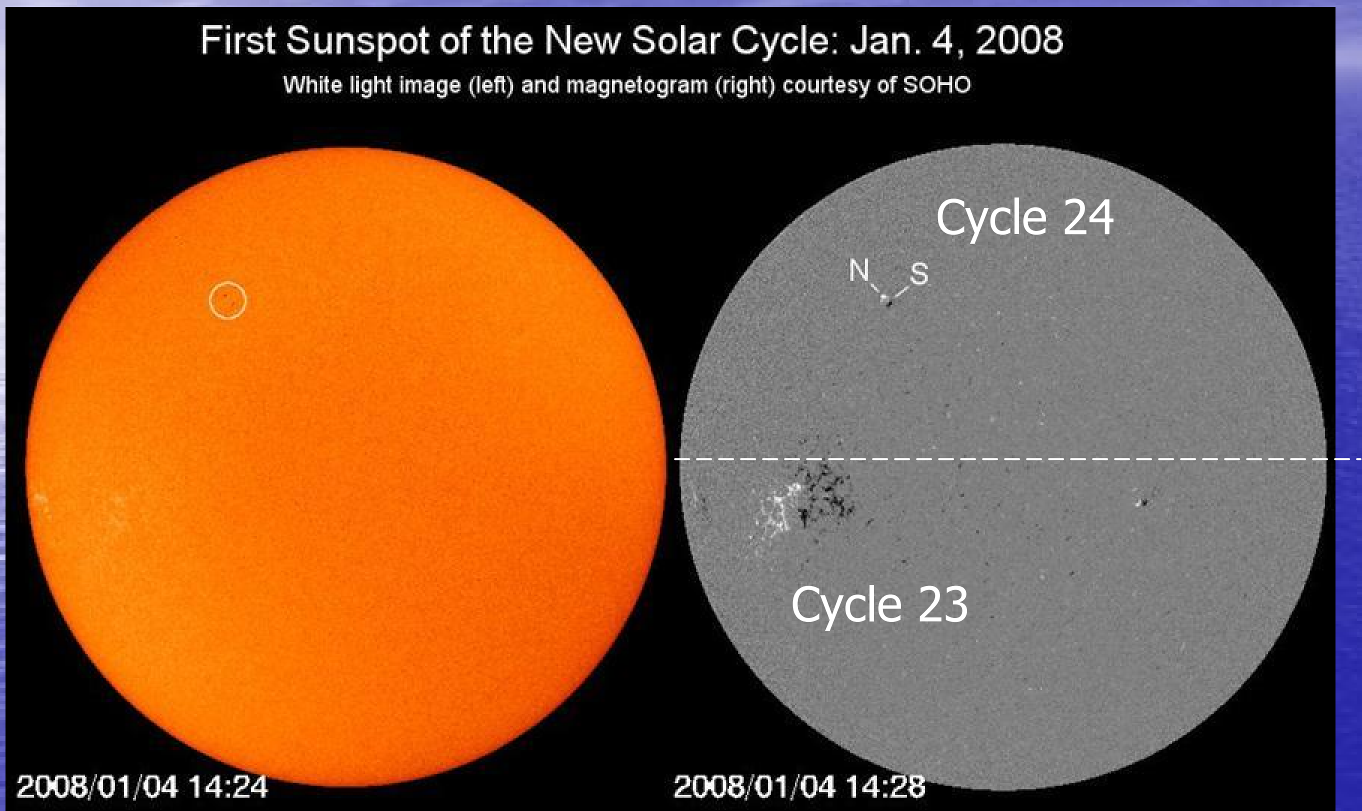
Long Term Look at Solar Activity



- ~ 88-year Gleissberg cycle
- ~ 205-year De Vries cycle
- ~ 2300-year Halstatt cycle (from Be^{10} in ice cores and C^{14} in tree rings)

- Reasonable sunspot records go back to the mid 1700s
- We can with reasonable accuracy reconstruct solar activity from cosmogenic nuclides
  - Be-10 in ice cores
  - C-14 in tree rings
  - Nuclides are high when solar activity is low, and vice versa
- There are several "cycles" to solar activity

Magnetograms



By convention, white is "outward" magnetic field line and black is "inward" magnetic field line

Magnetic fields are opposite from one solar cycle to the next

Magnetic fields are opposite in northern and southern hemisphere

Additional Info and Books for Your Library

K9LA's Propagation Web Site

- http://k9la.us
  - Timely Topics
  - Basic Concepts
  - Tutorials
  - General
  - 160 meters
  - HF
  - VHF
  - Contesting
  - Webinars

http://k9la.us

- Session 1 Formation of the Ionosphere
  - See "The Formation of the Ionosphere" and "The Structure of the ionosphere" in the General link
- Session 1 Measuring the Ionosphere
  - See "Measuring the Ionosphere" in the General link
- Session 1 Measuring the Ionosphere
  - See "The M-Factor" in the Basic Concepts link
- Session 1 Physics of Propagation from 150 KHz to 54 MHz
  - See "Polarization" in the General link
- Session 2 Propagation Examples at LF, MF, HF, VHF
  - See all the papers in the 160m link, the HF link, and the VHF link
  - See "160m Propagation" in the Webinars link

http://k9la.us

- Session 2 Propagation Predictions
  - See "Correlation Between Solar Flux and Sunspot Number", "Correlation Between MUF and Solar Flux", Validating Propagation Predictions in the Basic Concepts link
  - See "Downloading and Using VOACAP" and "Downloading and Using W6ELProp" in the Tutorials link
  - See "Propagation Prediction Programs – Their Development and Use" in the Webinars link
- Session 3 Disturbances to Propagation
  - See "Where Do the K and A index Come From?", "Disturbances to Propagation", and "A Look Inside the Auroral Zone" in the General link
  - See "Solar Flares at ZF2RR" and "CMEs at W4ZV" in the Contesting link
  - See "Disturbances to Propagation" in the Webinars link
- Session 3 Solar Cycles, A Review of Cycle 23, and Cycle 24 Update
  - See all the papers in the Timely Topics link

Additional Articles at k9la.us

- Noise
- Propagation to the Antipode
- Long Term Trends in the Ionosphere
- HF Propagation and the Airlines
- Propagation Planning for DXpeditions
- Trans-Equatorial Propagation
- Can the Ionosphere Fool Us?
- Dissecting a Skewed Path
- Magnetic Activity Indices
- Polar Mesosphere Summer Echoes
- QRP DXCC Honor Roll

Books for Your Library

- Introductory and moderate reading
  - The NEW Shortwave Propagation Handbook, Jacobs, Cohen, Rose, CQ Communcations
  - Radio Amateurs Guide to the Ionosphere, McNamara, Krieger Publishing Company
  - The Little Pistol's Guide to HF Propagation, Brown, WorldRadio books (available at http://k9la.us)
  - ARRL Antenna Book, Chapter 23, ARRL
- Technical reading
  - Ionospheric Radio, Davies, Peter Peregrinus Ltd