

The Carrington Event of 1859

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Rank Order of Geostorms from 1859 to Present

- Using recent and historical data of indicators for geomagnetic storms find the top contenders
 - Flare Size
 - Solar Energetic Proton (SEP) fluence
 - Sun-Earth disturbance transit time
 - Geomagnetic storm intensity
 - Low-latitude auroral extent
- Look in greater detail on the time evolution of the top storm; Aug. 31- Sept. 2, 1859


Flare Size*

- Solar Flare Effect (SFE) - direct flare induced ionization

Date	1-8 Class	Magnetometer Station	Zenith Angle ($\frac{1}{4}$)	SFE Amplitude (nT)
04 Nov 2003	X28	Newport	63	115
28 Feb 1942	?	Eskdalemuir	63	112
28 Oct 2003	>X17	Tamanrasset	36	111
01 Sep 1859	?	Greenwich	44	110
15 Jun 1991	>X12	Hyderabad	22	95
06 Jun 1991	>X12	Guam	20	90
15 Apr 2001	>X15	Tamanrasset	34	85

[* Cliver and Svalgaard, Solar Physics, 2004]

Solar Energetic Protons

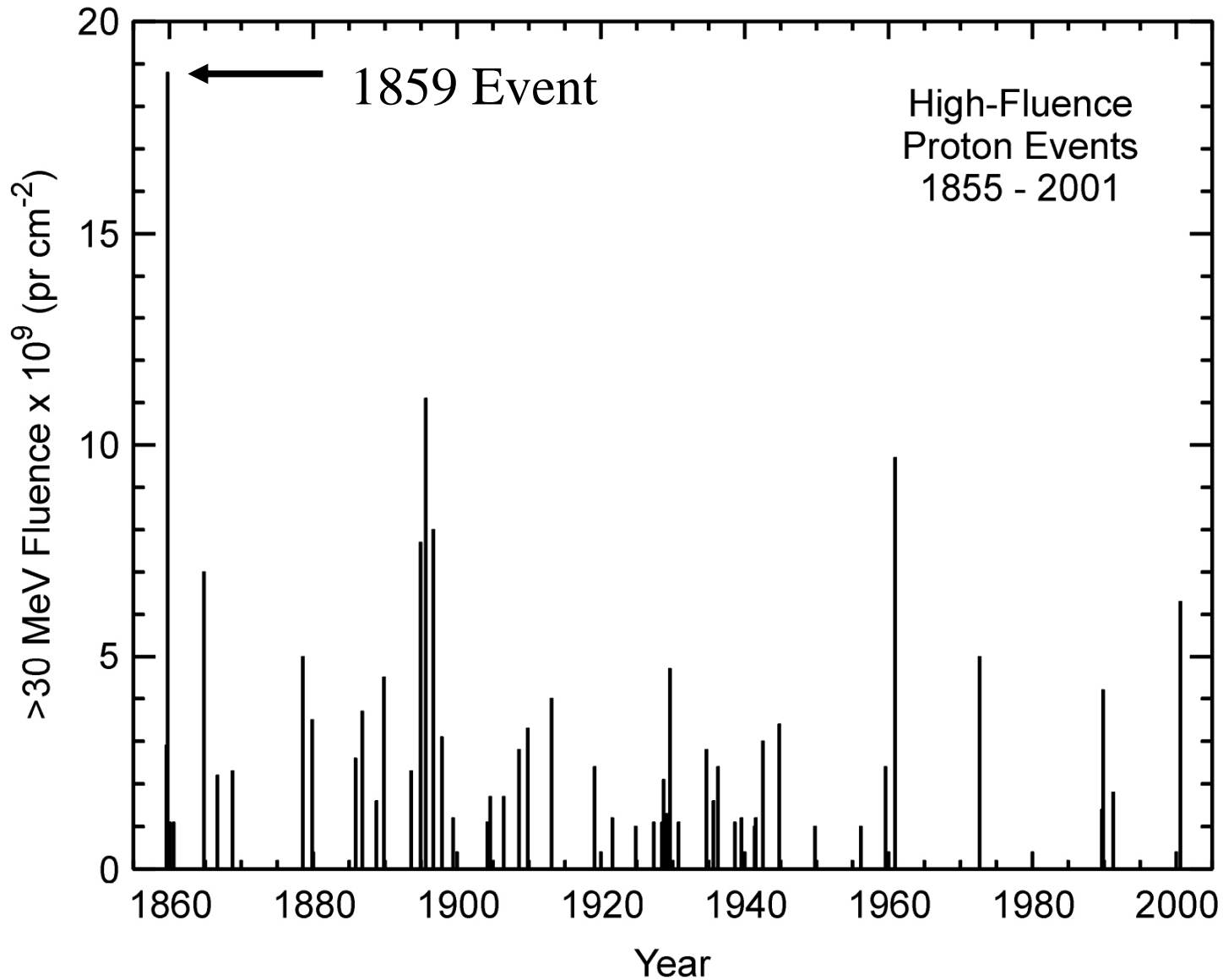


Date*	> 30 MeV SEP fluence (10^9 pr cm^{-2})
Aug-Sep 1859	18.8
1895	11.1
Nov 1960	9.7
1896	8.0
1894	7.7
1864	7.0
Jul 2000	6.3
1878	5.0
Aug 1972	~ 5

* Only year given for events without identified candidate sources.

From nitrate composition in ice cores [McCracken et al., 2001]

Solar Proton Events



“Fast-transit” solar wind events, 1859-2003



Flare Date	Transit Time (hr)	References
04 Aug 1972	14.6	1,2,3
01 Sep 1859	17.6	4,5,6,7,8
06 Feb 1946	17.8	3,9
28 Feb 1941	18.4	10
16 Jul 1959	19.4	11
28 Feb 1942	19.5	8,12
17 Sep 1941	19.8	8,13
29 Oct 2003	~20*	14
28 Oct 2003	20.3*	14
15 Apr 1938	21.2	8,15
12 Nov 1960	21.2	11
16 Jan 1938	21.8	15,16

References: (1) Dryer et al., 1975; (2) Vaisberg and Zastenker, 1976; (3) Cliver et al., 1990b; (4) Carrington, 1860; (5) Hodgson, 1860; (6) Hale, 1931; (7) Bartels, 1937; (8) Newton, 1943; (9) Nicholson and Hickox, 1946; (10) Newton, 1941a; (11) Ellison, McKenna, and Reid, 1961; (12) Newton, 1942; (13) Newton, 1941b; (14) Skoug et al., 2004; (15) Bartels, 1940; (16) Bartels, Heck, and Johnston, 1939.

Top Storms Recorded at Greenwich/Abinger, 1859-1954

Date	Ranges		
	Declination	Horizontal Force (nT)	Vertical (nT)
01 Sep 1859	>>92	>>625	1500
04 Feb 1872	125	800	>950
17 Nov 1882	115	>1090	>1060
31 Oct 1903	119	1175	1440
25 Sep 1909	193	1710	>1080
14 May 1921	110	>>740	>>460
25 Jan 1938	126	1055	570
16 Apr 1938	307	1375	500
24 Mar 1940	131	1370	1000
01 Mar 1941	186	1650	1310
18 Sep 1941	123	1250	1115
28 Mar 1946	162	1660	920
21 Sep 1946	136	925	450

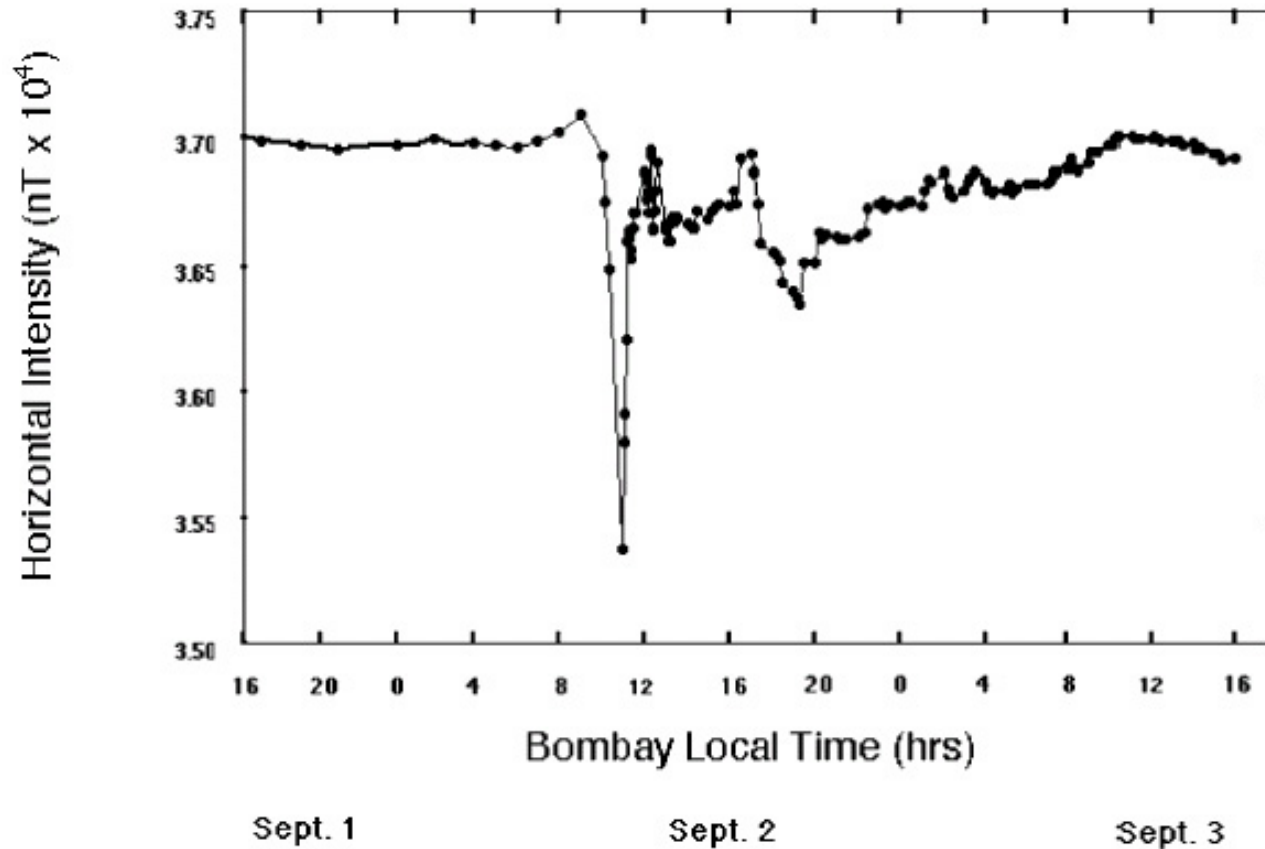


Top 25 Storms based on DST



Date	Time (UT hr)	Peak Value (nT)
2 Sept 1859	05	-1760
14 Mar 1989	01	-548
05 Jul 1941	13	-453
28 Mar 1946	14	-440
15 Jul 1959	19	-434
11 Feb 1958	11	-428
13 Sep 1957	10	-426
26 May 1967	04	-391
31 Mar 2001	08	-383
01 Mar 1941	18	-382
09 Nov 1991	01	-375
24 Mar 1940	20	-366
19 Sep 1941	06	-359
25 Jan 1938	23	-352
26 Jan 1949	00	-350
22 Jan 1938	11	-344
08 Jul 1958	20	-334
13 Nov 1960	09	-333
30 Apr 1960	18	-325
01 Apr 1960	18	-325
05 Sep 1957	03	-324
14 Jul 1982	03	-322
04 Sep 1958	22	-305
23 Sep 1957	07	-302
16 Jul 2000	00	-301
25 Mar 1991	00	-297

DST for the 1859 Great Storm



- Reanalysis of the Bombay, India magnetometer observations
 - DST of -1760 nT (Tsurutani et al. [2003])

Low Latitude Auroras, 1859-1958

Date	Low Latitude Extent	Reference
→ 2 September 1859	18¼	Loomis (1859, 1860a,b, 1861); Kimball (1960), Green and Boardsen (2005)
4 February 1872	19¼	Chapman (1957a,b)
11 February 1958	28¼	Adem (1958)
14 May 1921	30¼	Silverman and Cliver (2001)
25 September 1909	30¼	Silverman (1995)
25 January 1938	30¼	S. Silverman (personal Communication, 2004)

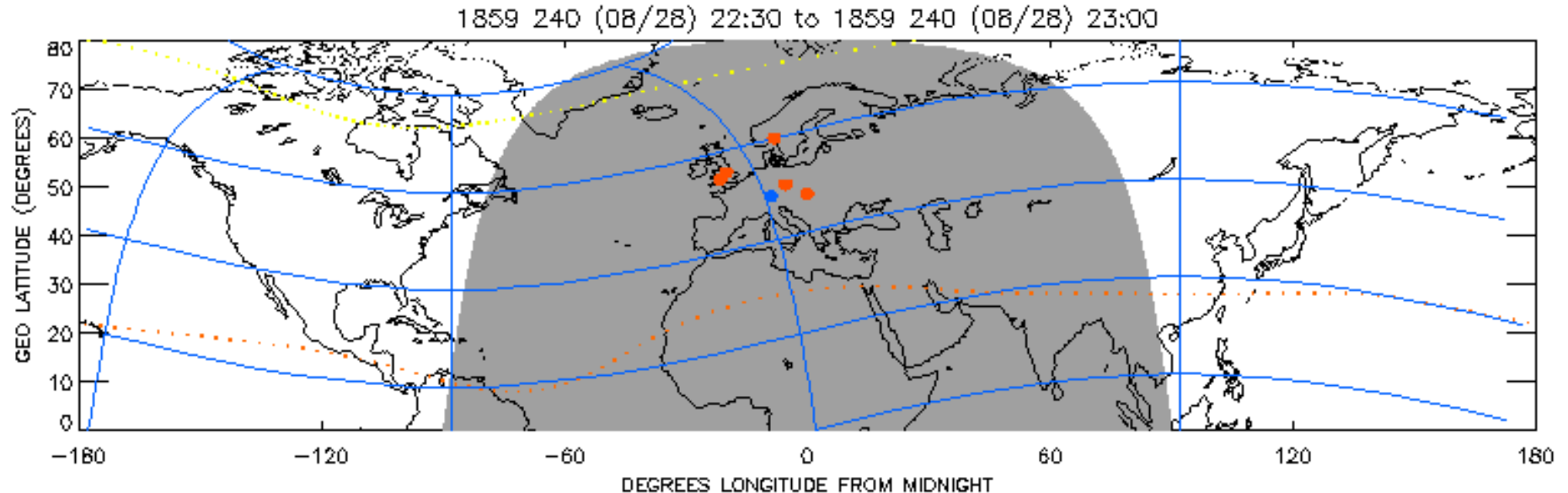
Survey Results

- Taken together, the top-ranking events in each of the disturbance categories comprise a set of benchmarks for extreme space weather activity
- While the 1859 event has close rivals or superiors in each of the above categories of space weather activity, it is the only documented event of the last ~150 years that ranks at or near the top on all of the lists.
- A time history of ground-based auroral and magnetic observations of the 1859 is of special interest
 - Necessary to provide input for computer simulations of the event
 - Will lead to a realistic range of solar wind parameters

Observations Used in This Study

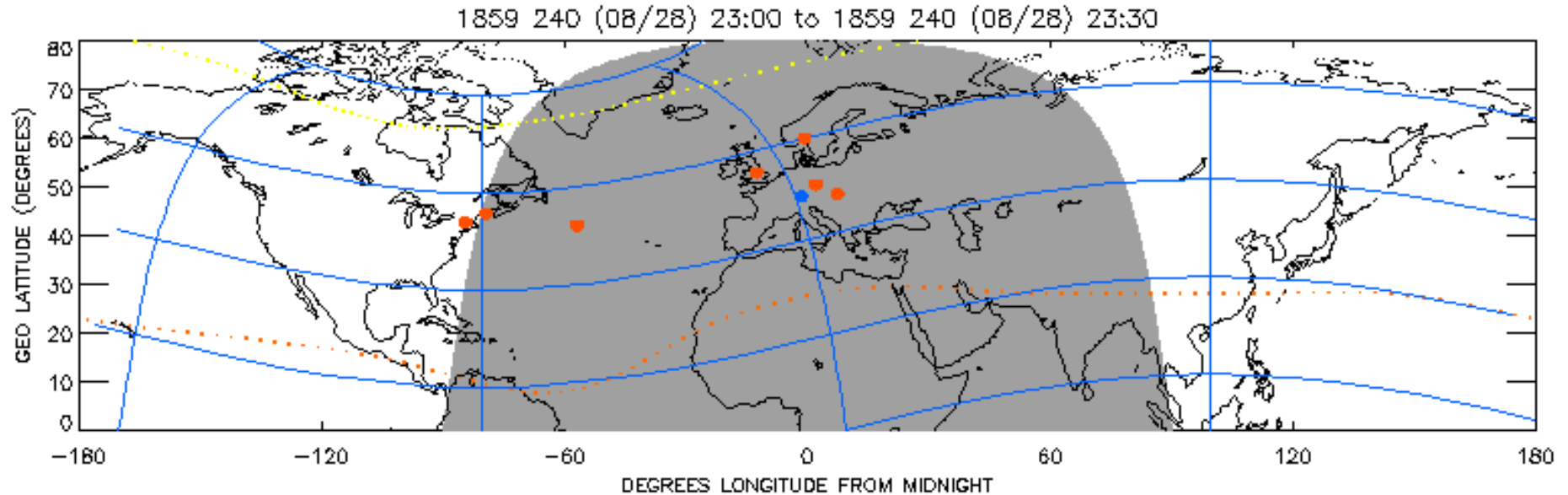
- Published scientific observations of the aurora and ground-based magnetometer data
 - Journal publications (Loomis, Am J. Sci, '59, '60abc, '61ab, '65)
 - Observatory notes
- Eyewitness accounts of the aurora:
 - Newspapers around the world (reviewed ~1000 papers)
 - Manuscripts and books
 - Ship deck logs - required by international agreements to record observations of aurora
- Constraints:
 - Only observations in which location, start-stop times, and auroral descriptions are used
 - Several hundred reports were selected and data-based

August 28-29, 1859 Event



- Location of eyewitness auroral observations (red), extreme magnetometer deviations (blue)
 - Local time of the observation converted to UT
- Mercator projection with a nightside view
 - Geomagnetic (dipole) latitude/longitude shown
- Minimum and maximum extent of the oval (Holzworth-Meng) 13

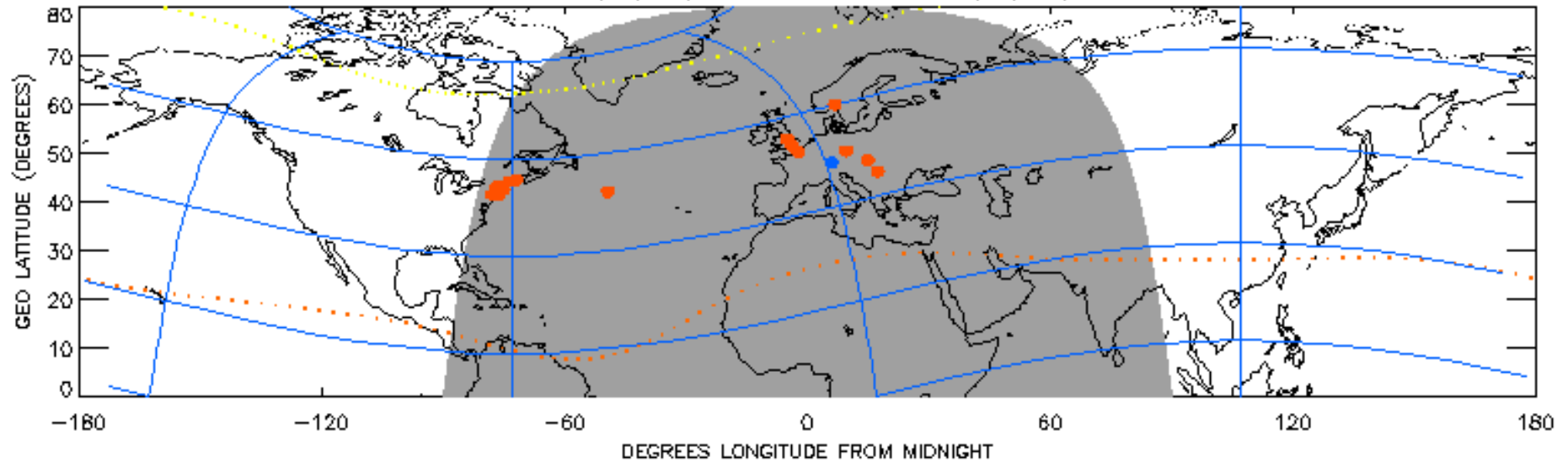
August 28-29, 1859 Event



- New moon (partial solar eclipse) occurred on Aug. 28th

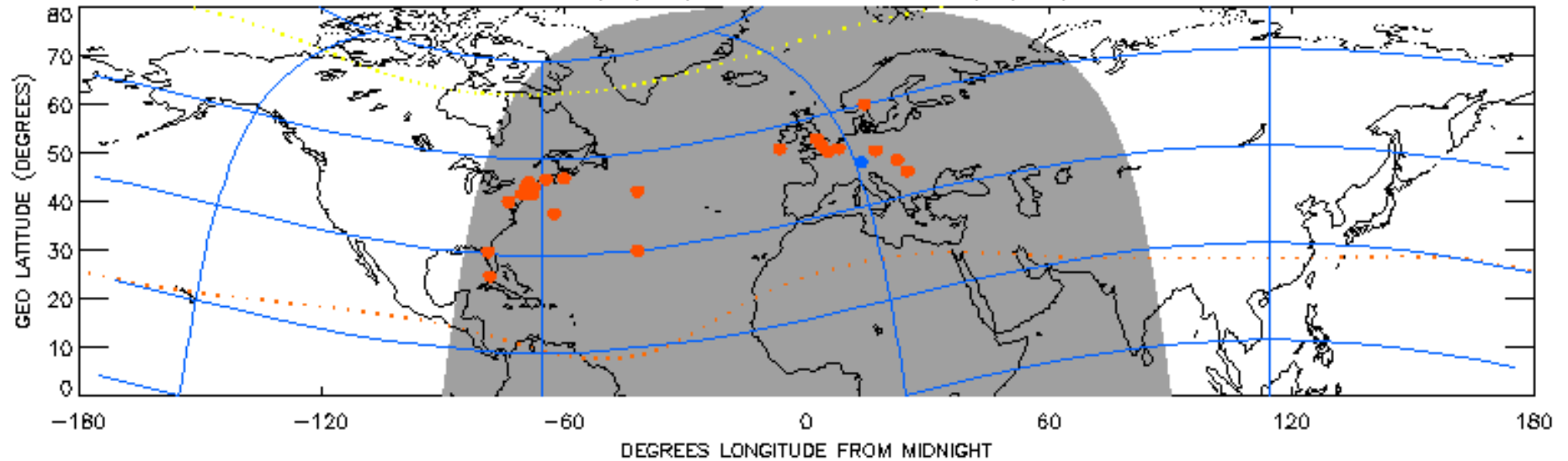
August 28-29, 1859 Event

1859 240 (08/28) 23:30 to 1859 241 (08/29) 00:00

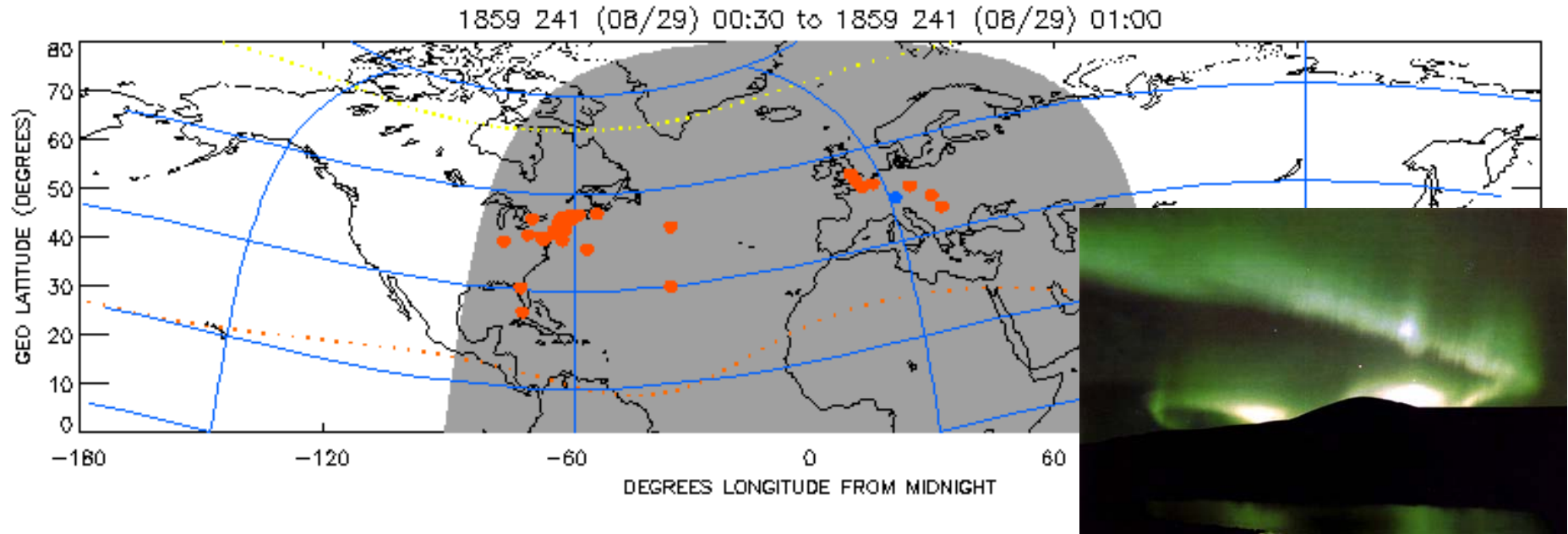


August 28-29, 1859 Event

1859 241 (08/29) 00:00 to 1859 241 (08/29) 00:30

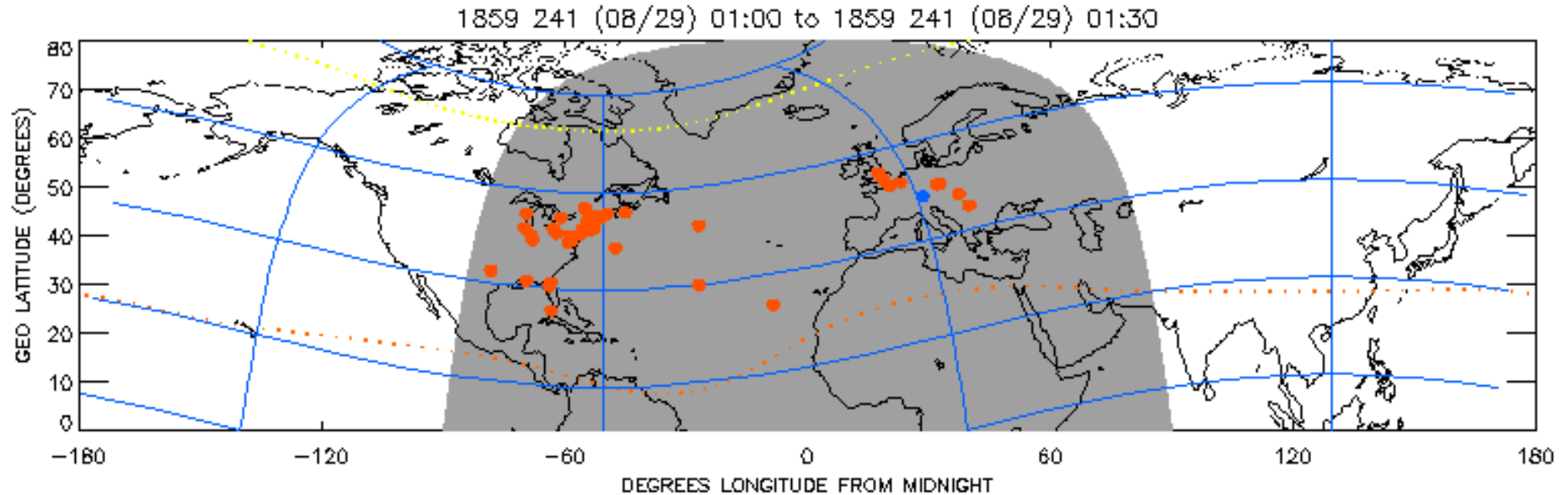


August 28-29, 1859 Event



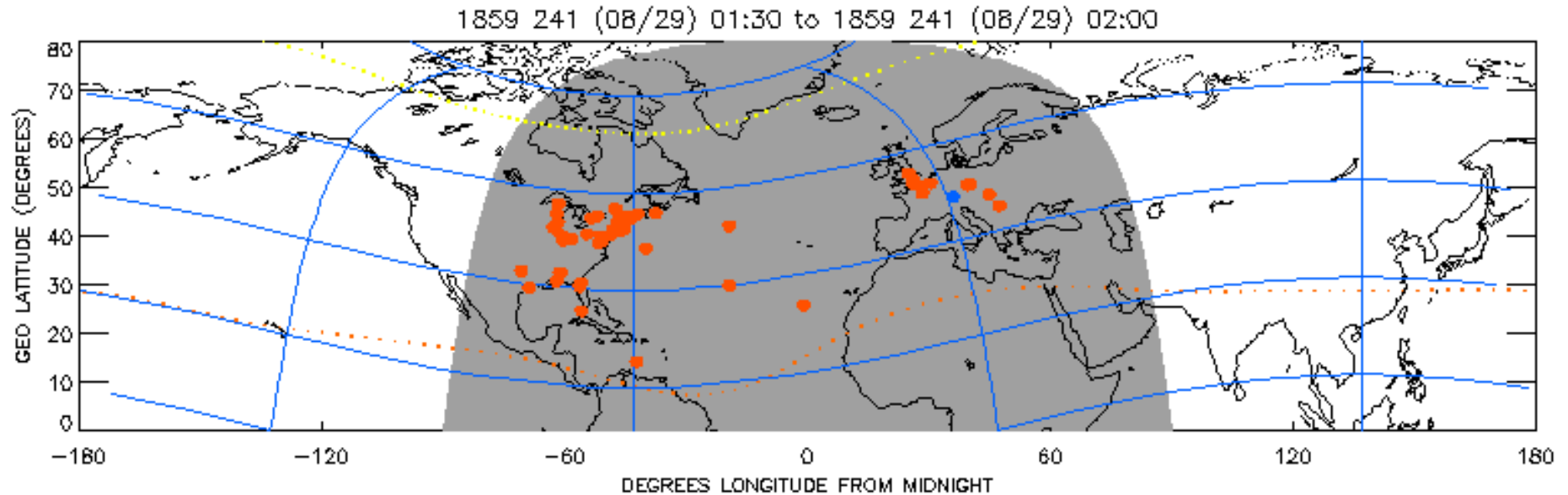
- Cleveland Ohio - “...a bright lurid light, such as in frequently seen at sunset ...making it as light as the moon at half full”

August 28-29, 1859 Event



- Induced currents on telegraph lines (~140,000 miles) in Europe and the US render many of them useless

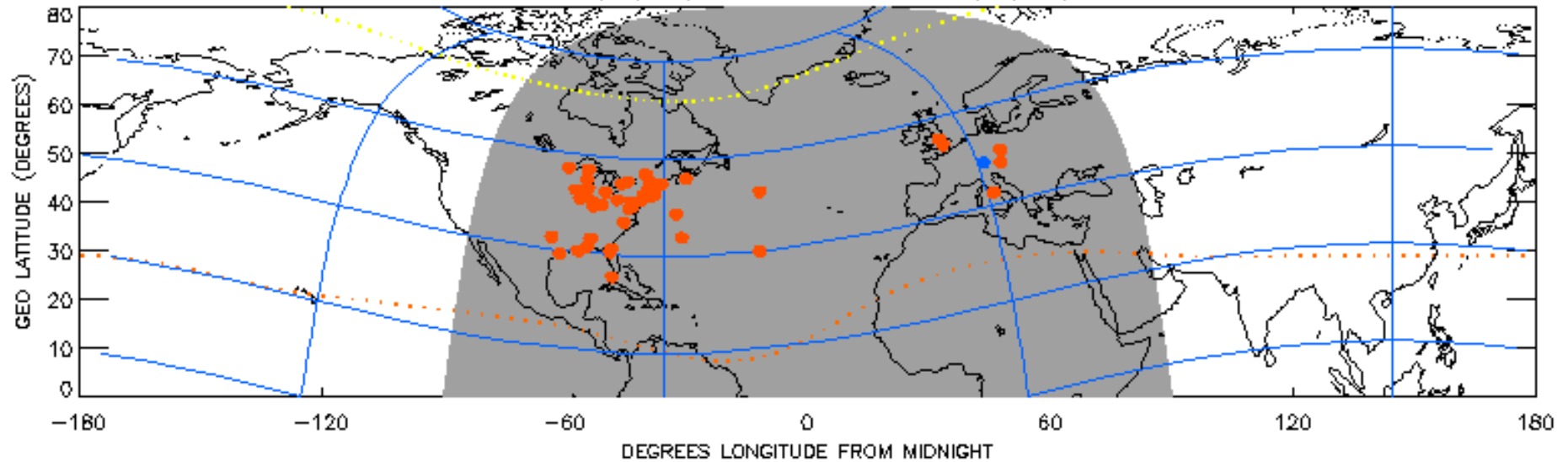
August 28-29, 1859 Event



- Greytown (deck log: Lat. 12°) - “... discovered a very bright red light, bearing due north and easterly over an arc of the horizon of about 70° with an altitude of about 20° .”

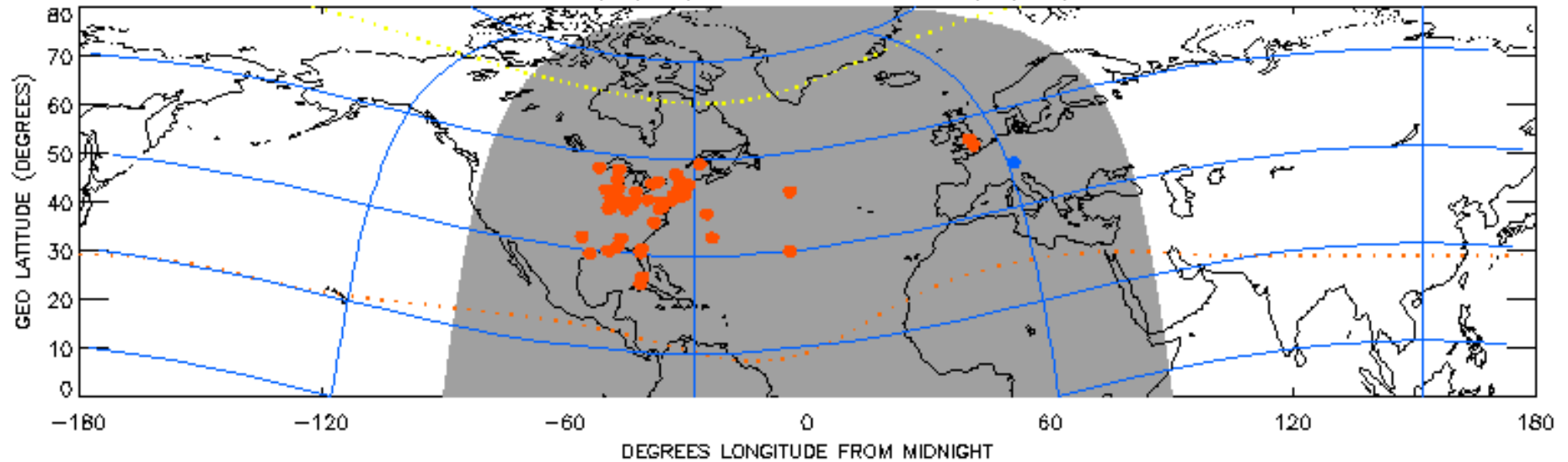
August 28-29, 1859 Event

1859 241 (08/29) 02:00 to 1859 241 (08/29) 02:30



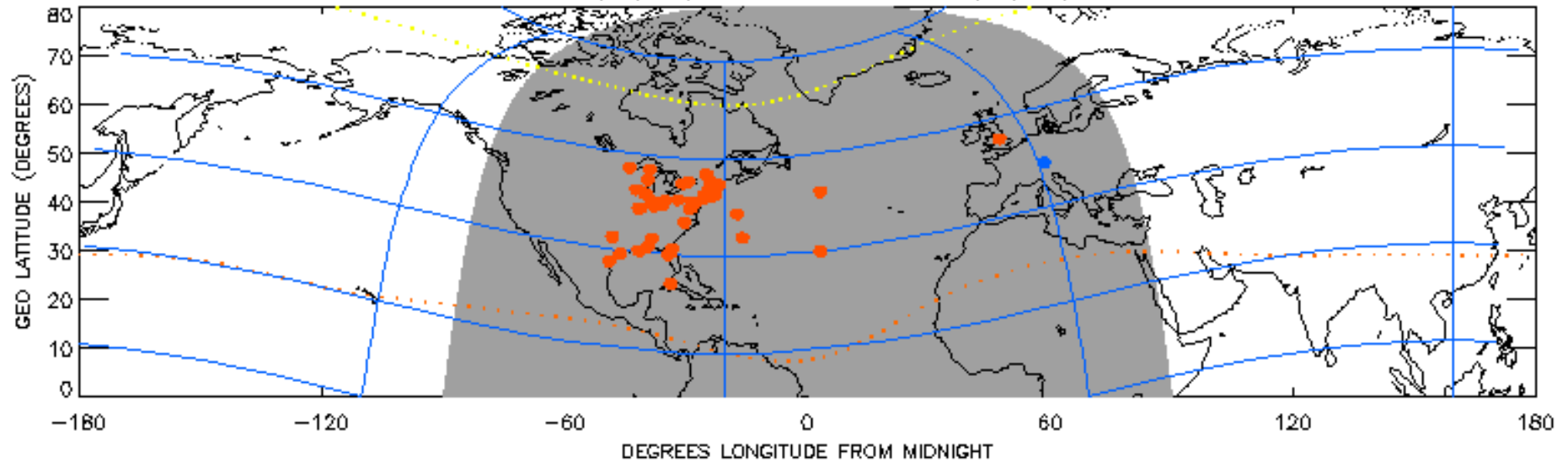
August 28-29, 1859 Event

1859 241 (08/29) 02:30 to 1859 241 (08/29) 03:00



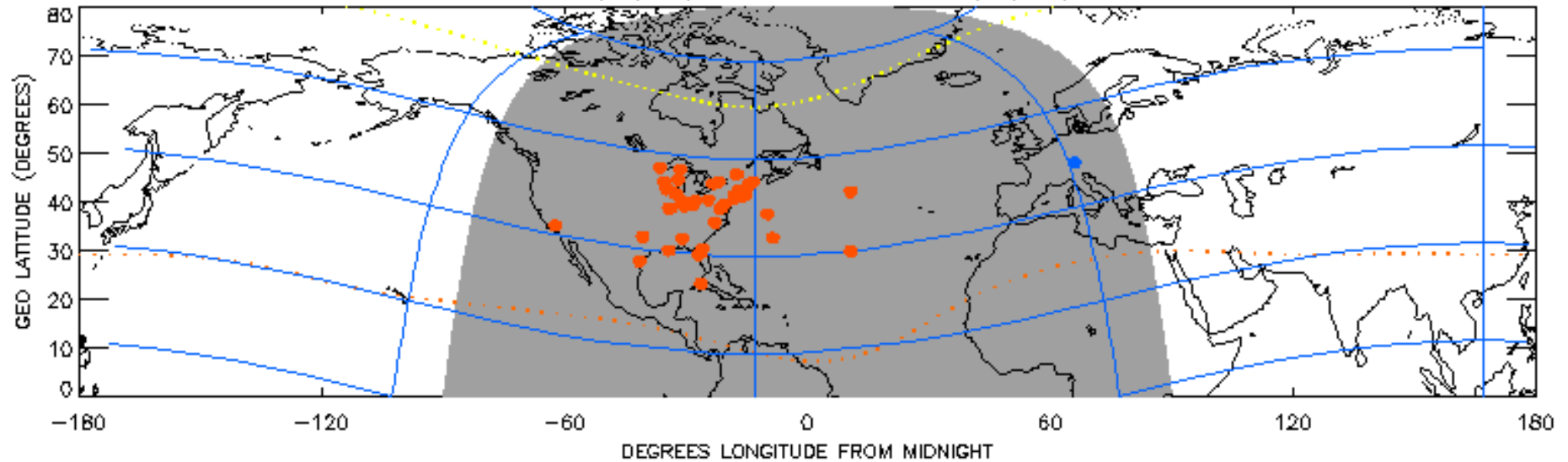
August 28-29, 1859 Event

1859 241 (08/29) 03:00 to 1859 241 (08/29) 03:30

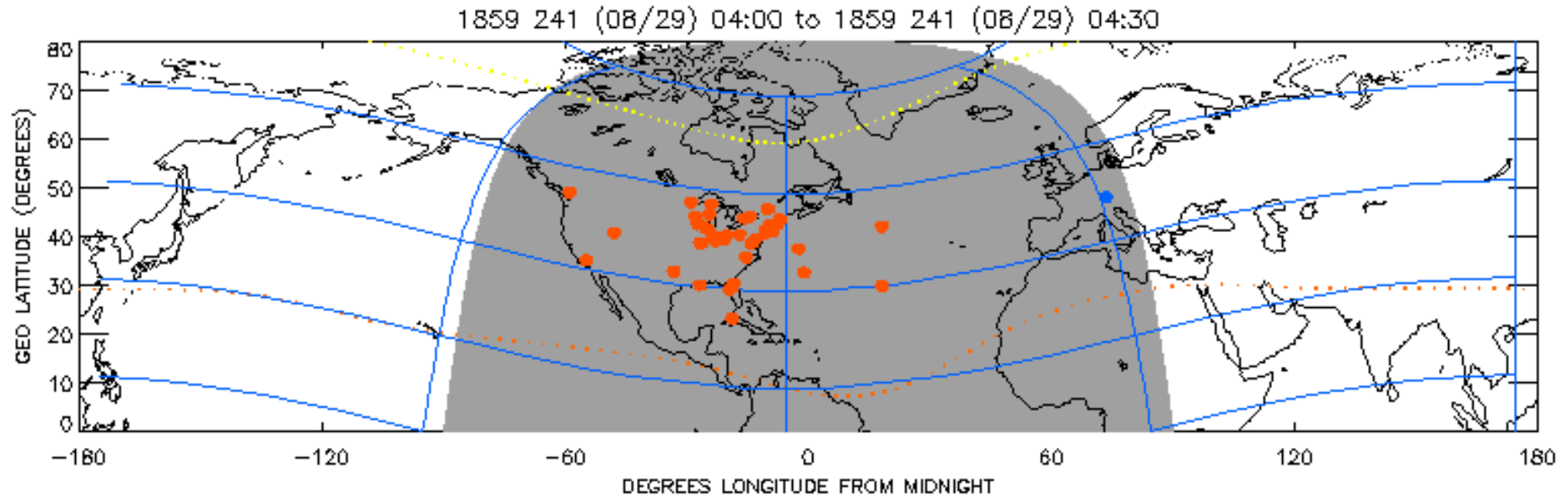


August 28-29, 1859 Event

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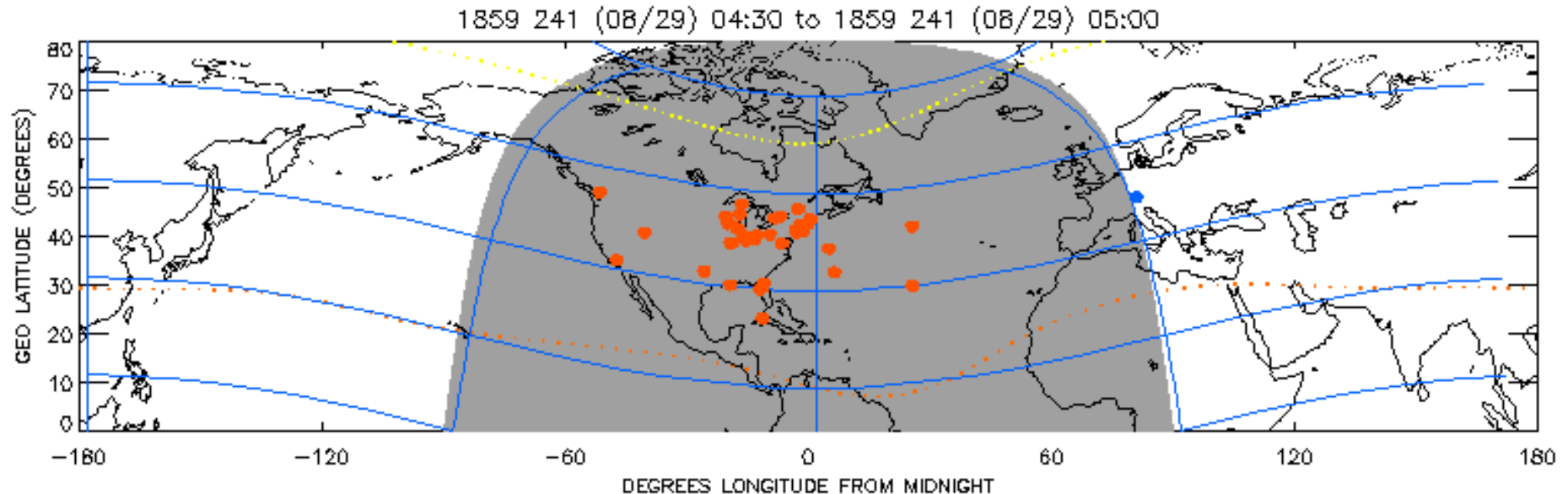


August 28-29, 1859 Event



- Release (deck log: 39°)- “the heaven became illuminated with a crimson glow passing from the North and West to the South supposed to be the northern lights”

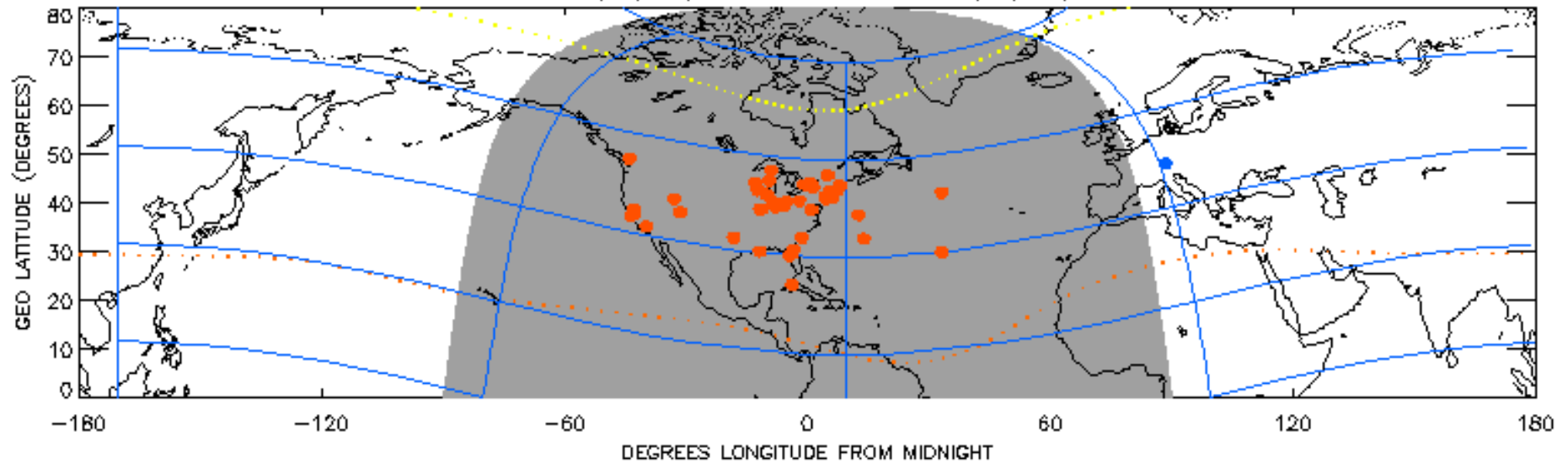
August 28-29, 1859 Event



- New Orleans - “sheets of the same white luminous cloud again illuminated the sky, producing about the same amount of light as the full moon, and the night became almost as the day...”

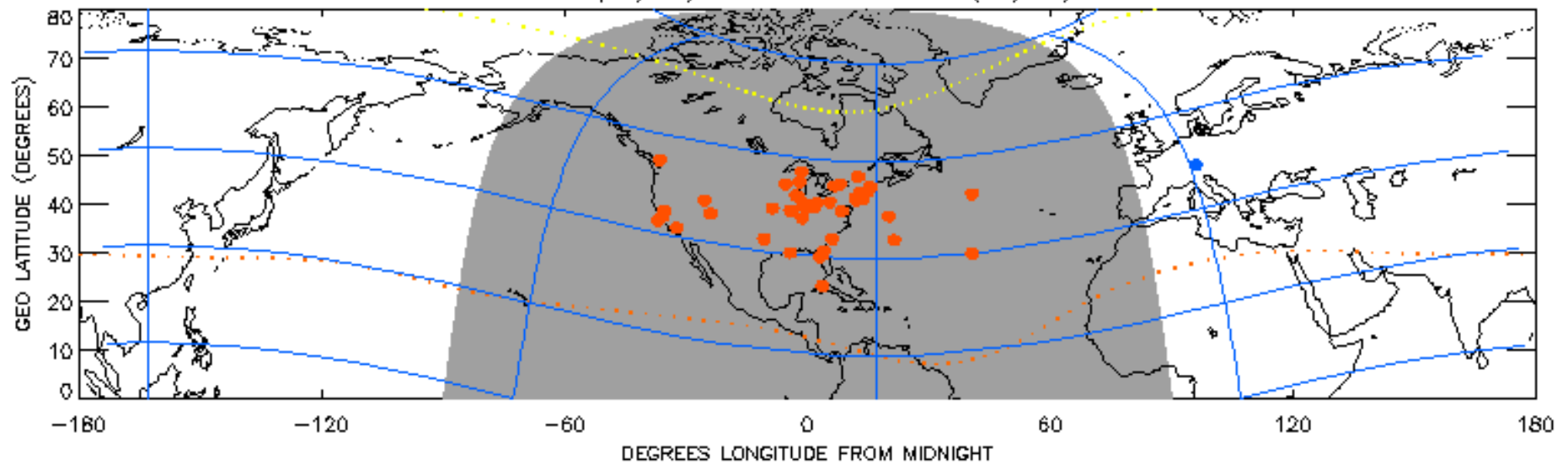
August 28-29, 1859 Event

1859 241 (08/29) 05:00 to 1859 241 (08/29) 05:30



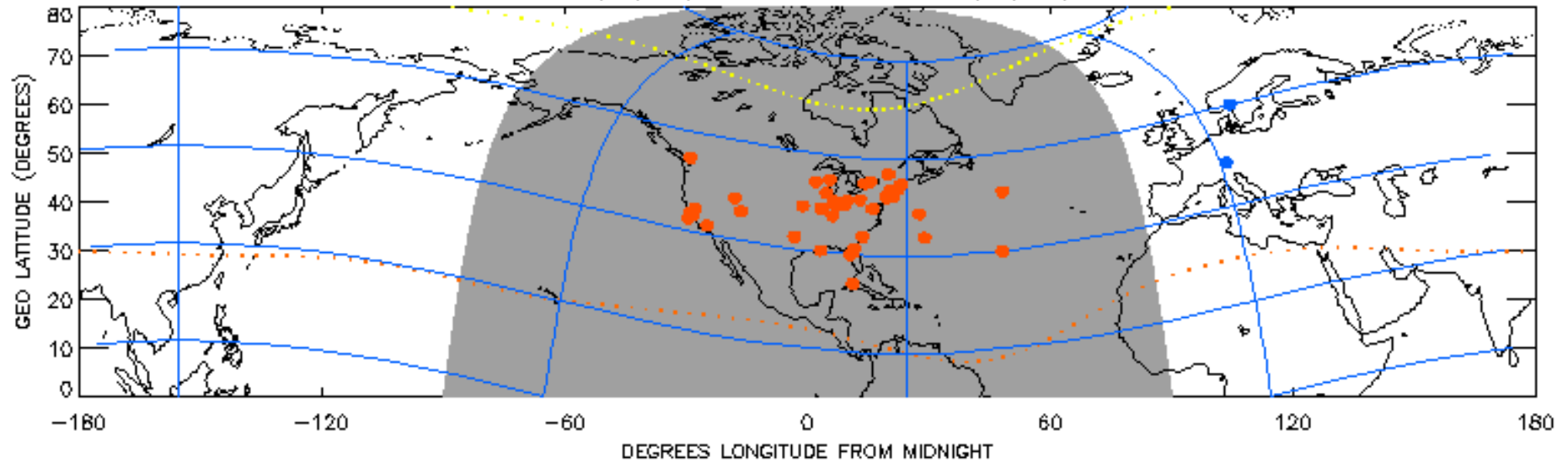
August 28-29, 1859 Event

1859 241 (08/29) 05:30 to 1859 241 (08/29) 06:00



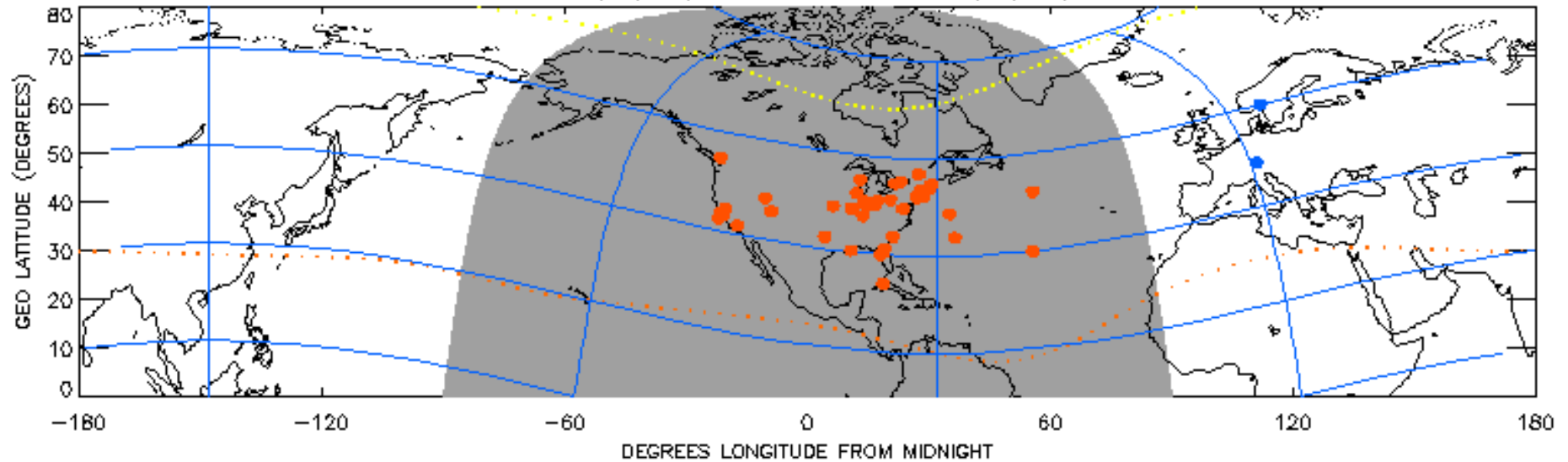
August 28-29, 1859 Event

1859 241 (08/29) 06:00 to 1859 241 (08/29) 06:30

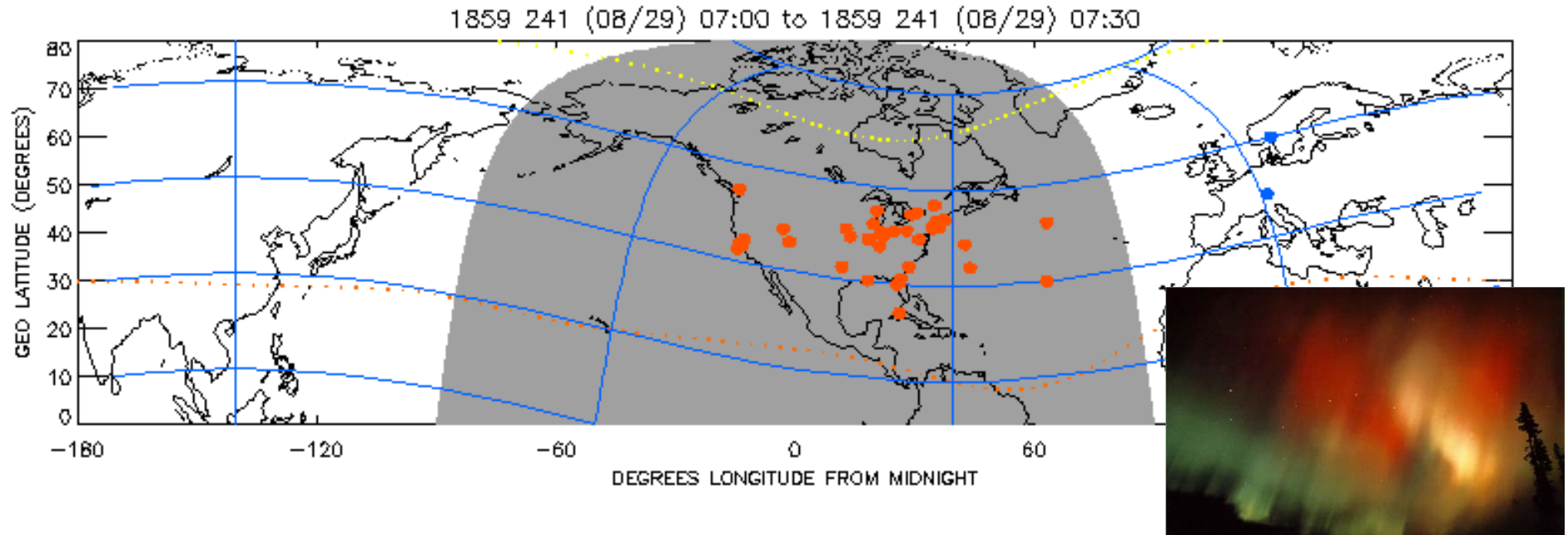


August 28-29, 1859 Event

1859 241 (08/29) 06:30 to 1859 241 (08/29) 07:00



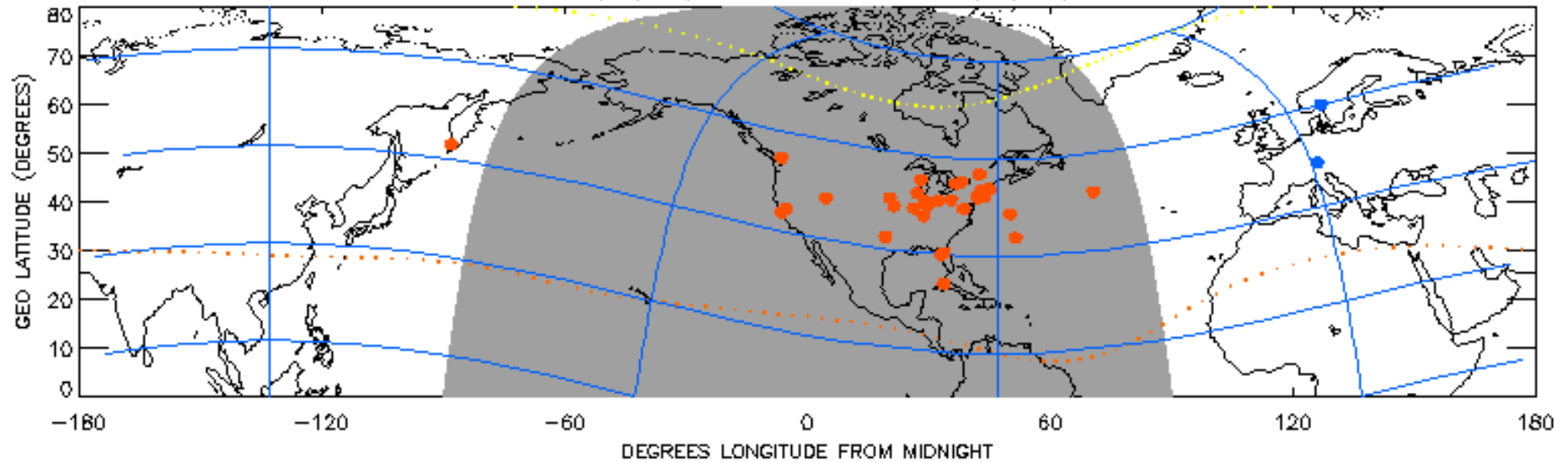
August 28-29, 1859 Event



- New York Herald - “At one time ...the heavens assumed an almost blood red appearance, while here and there long streaks of light shot up from the horizon to the zenith.”

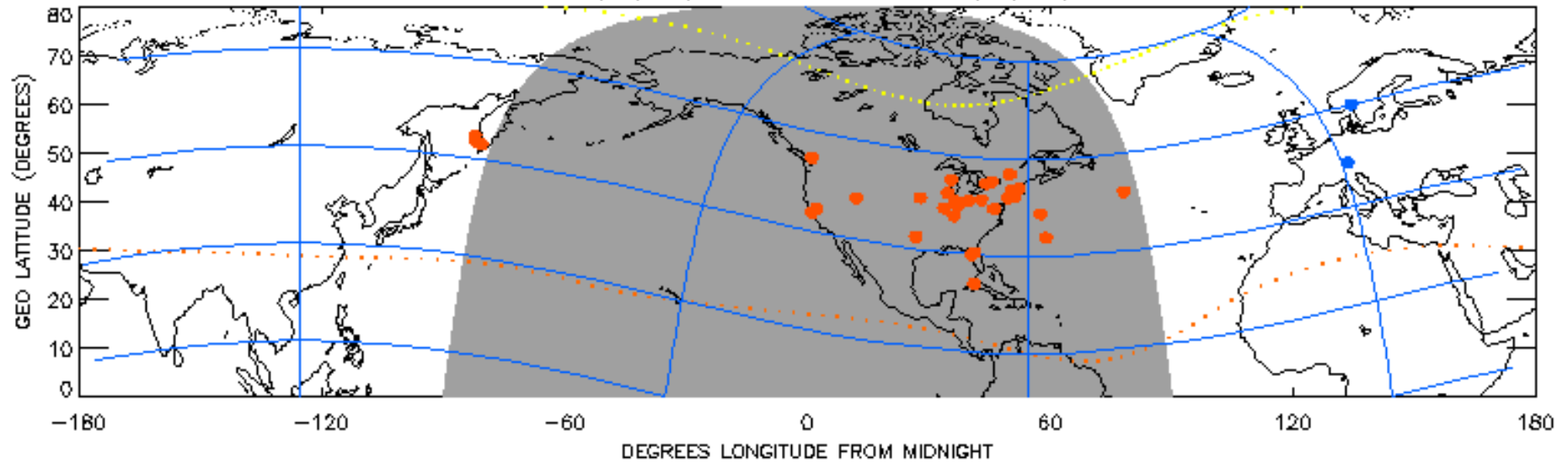
August 28-29, 1859 Event

1859 241 (08/29) 07:30 to 1859 241 (08/29) 08:00



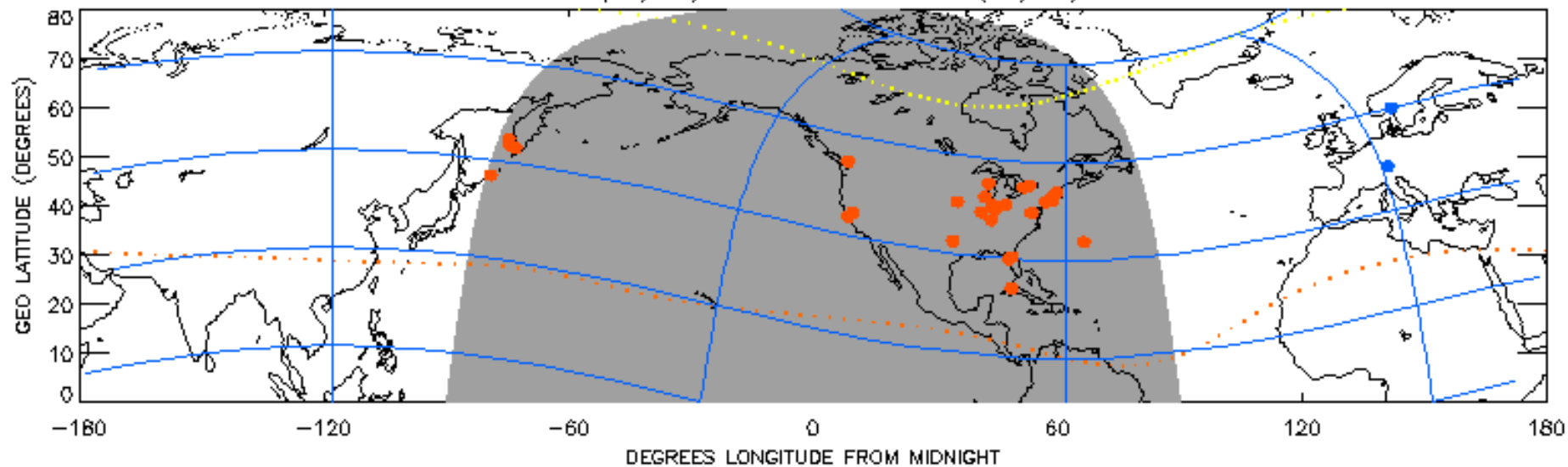
August 28-29, 1859 Event

1859 241 (08/29) 08:00 to 1859 241 (08/29) 08:30



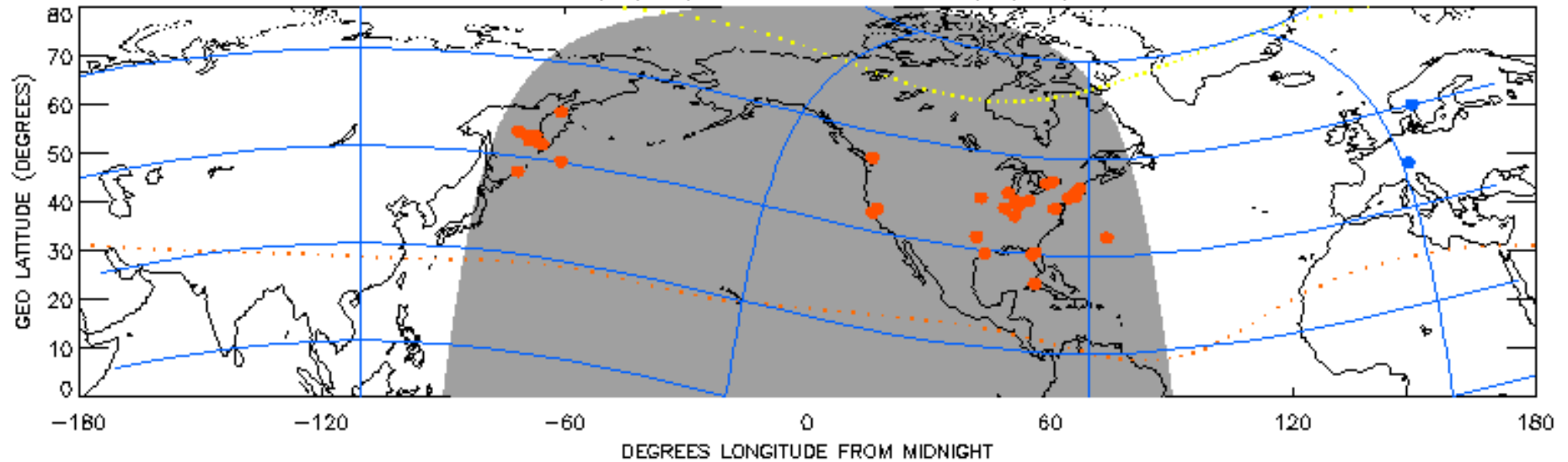
August 28-29, 1859 Event

1859 241 (08/29) 08:30 to 1859 241 (08/29) 09:00



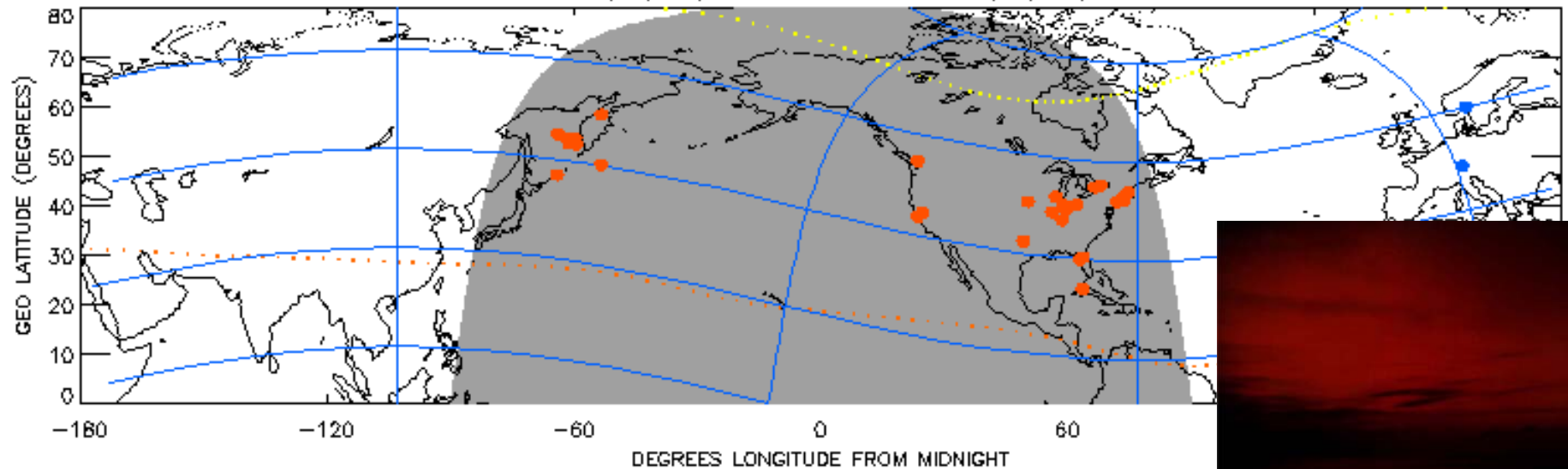
August 28-29, 1859 Event

1859 241 (08/29) 09:00 to 1859 241 (08/29) 09:30



August 28-29, 1859 Event

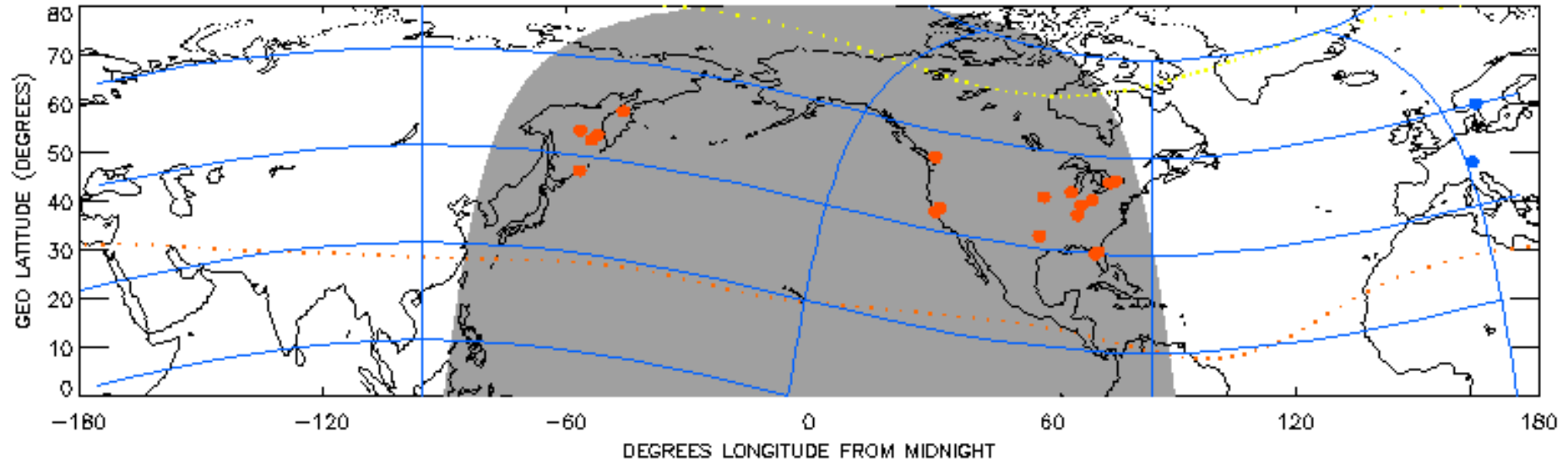
1859 241 (08/29) 09:30 to 1859 241 (08/29) 10:00



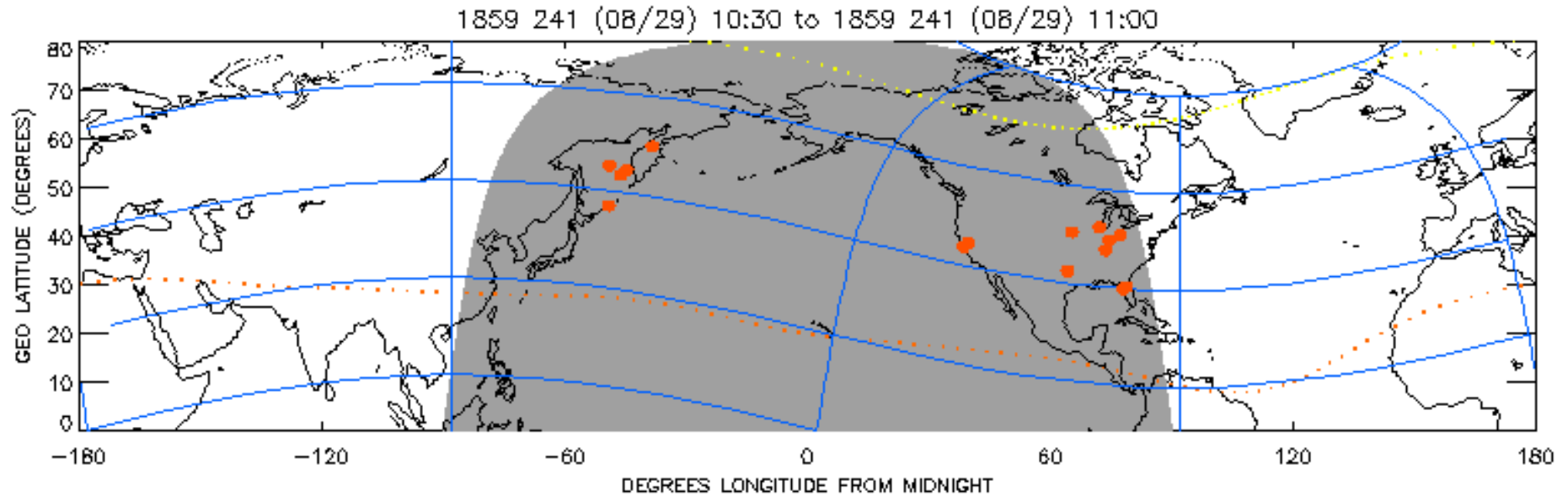
- Cleveland Ohio -” ...the light began to assume a delicate pink tinge, ...its change was followed by all the sky, until the entire vault of heaven had this delicate color. This continued to grow darker, first to scarlet, then to crimson, and finally to the blood-red like appearance of an immense conflagration. ”

August 28-29, 1859 Event

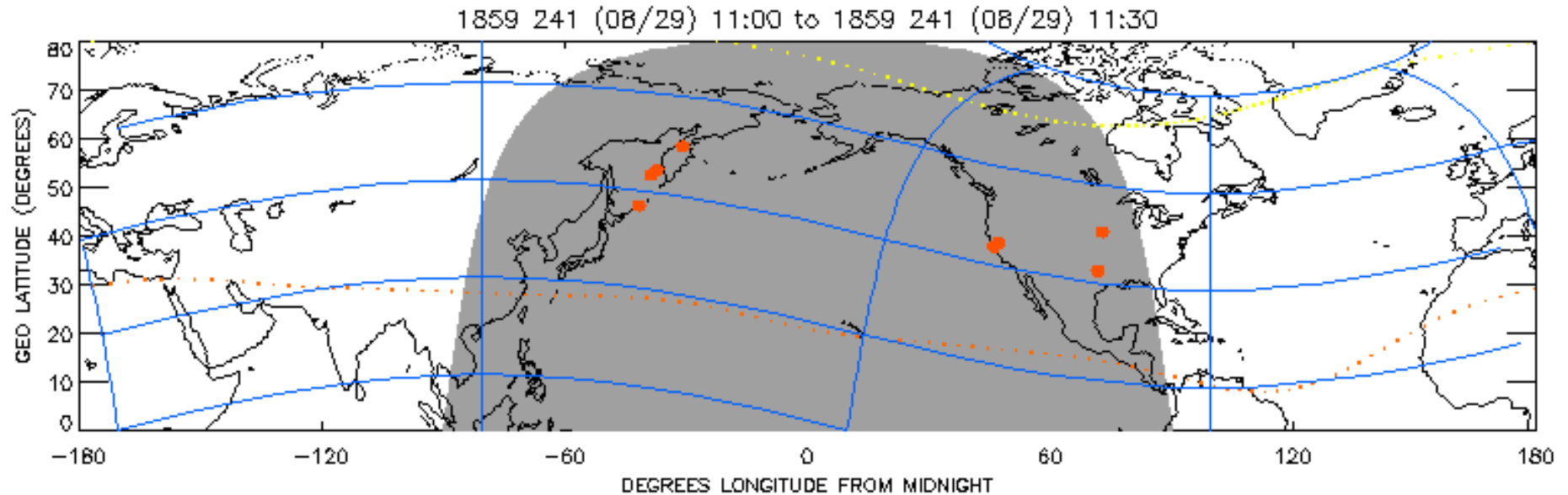
1859 241 (08/29) 10:00 to 1859 241 (08/29) 10:30



August 28-29, 1859 Event

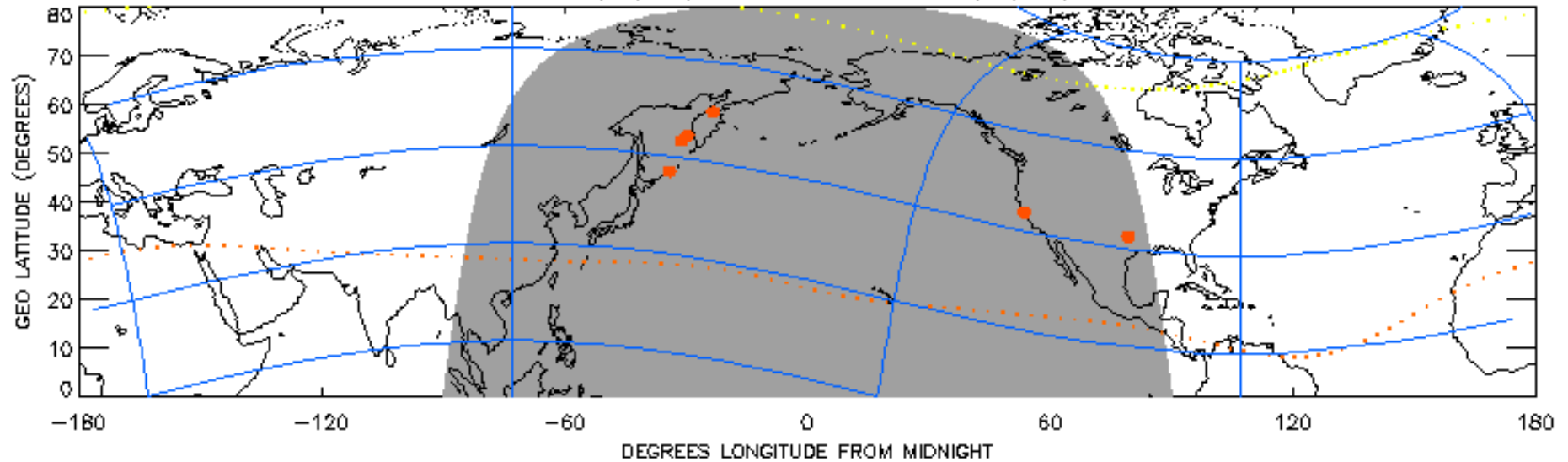


August 28-29, 1859 Event

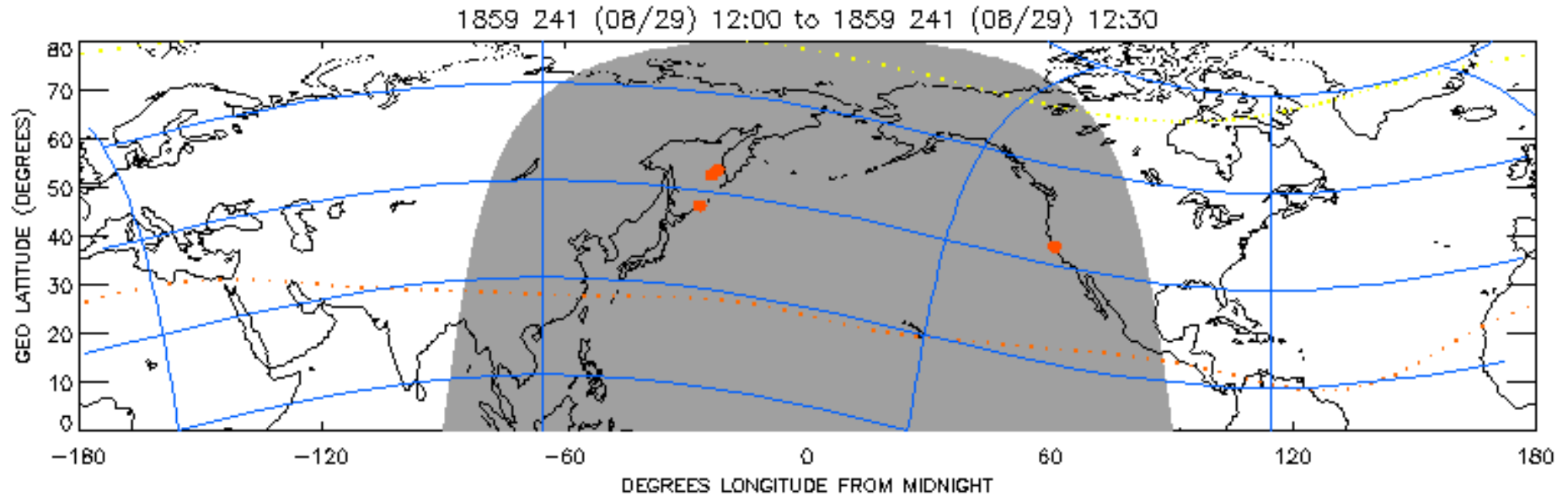


August 28-29, 1859 Event

1859 241 (08/29) 11:30 to 1859 241 (08/29) 12:00

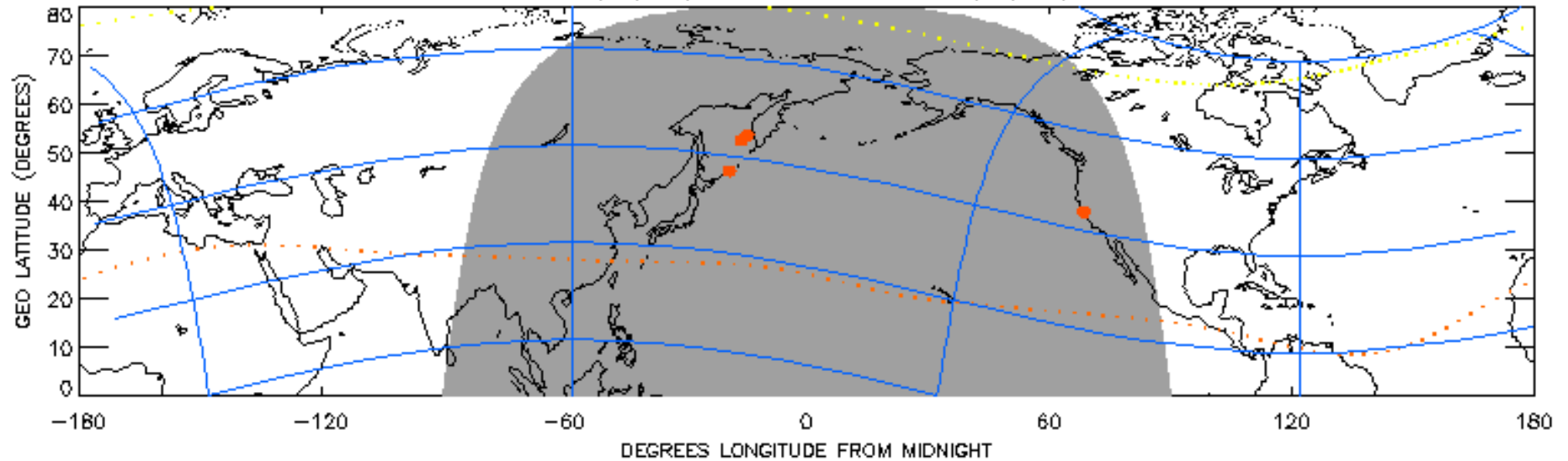


August 28-29, 1859 Event



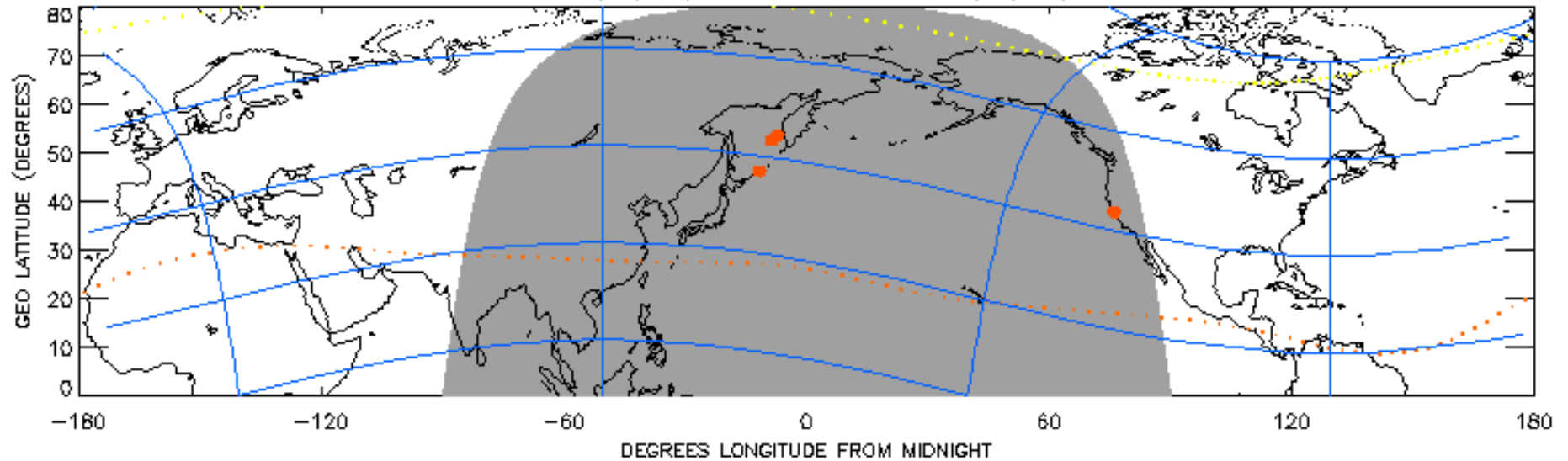
August 28-29, 1859 Event

1859 241 (08/29) 12:30 to 1859 241 (08/29) 13:00



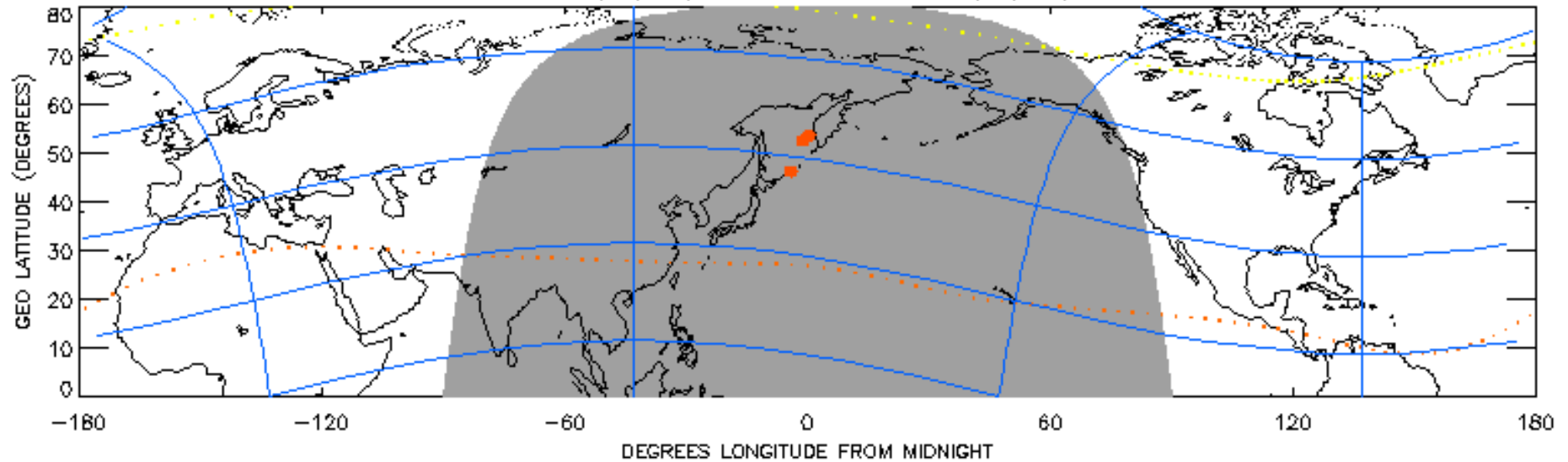
August 28-29, 1859 Event

1859 241 (08/29) 13:00 to 1859 241 (08/29) 13:30



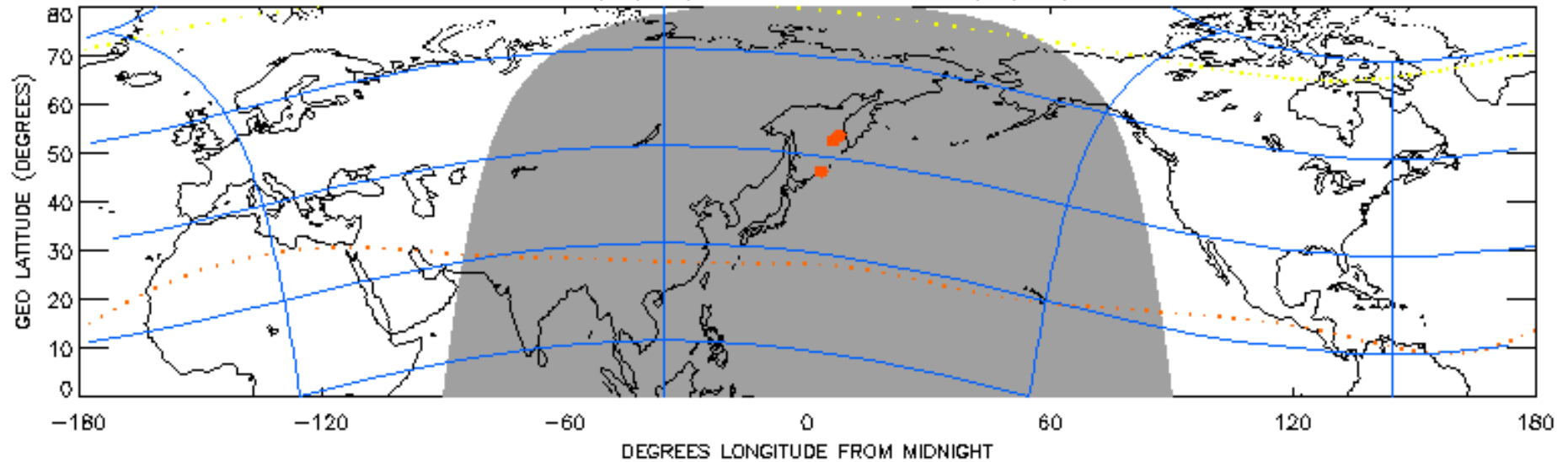
August 28-29, 1859 Event

1859 241 (08/29) 13:30 to 1859 241 (08/29) 14:00



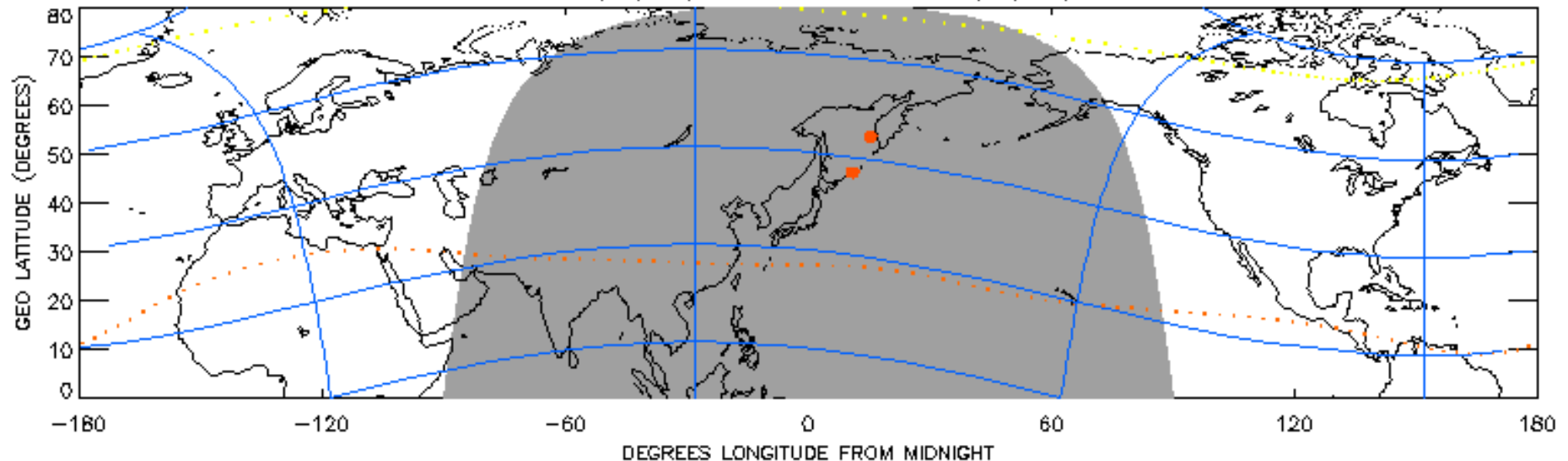
August 28-29, 1859 Event

1859 241 (08/29) 14:00 to 1859 241 (08/29) 14:30



August 28-29, 1859 Event

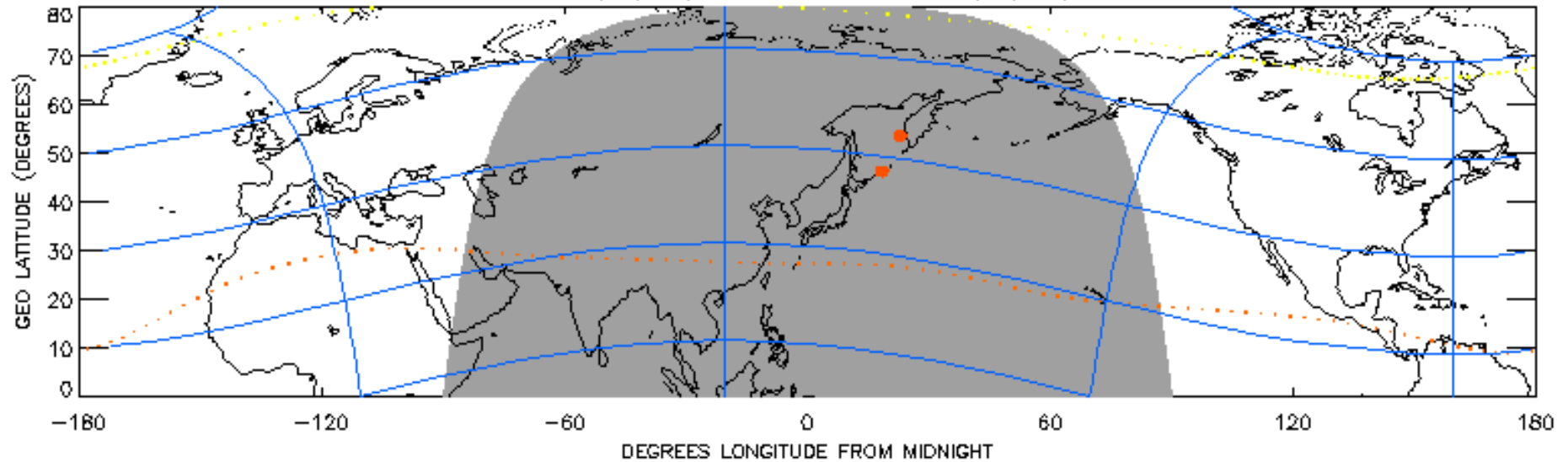
1859 241 (08/29) 14:30 to 1859 241 (08/29) 15:00



- Baltimore American - “Skilled telegraph operators worked incessantly from 8PM on the 28th until 10AM on the 29th to successfully transmit only about 400 words of a press report. At some stations it was impossible to send messages even to their nearest neighbors for 10 or more hours, while at others, the outage was only temporary.”

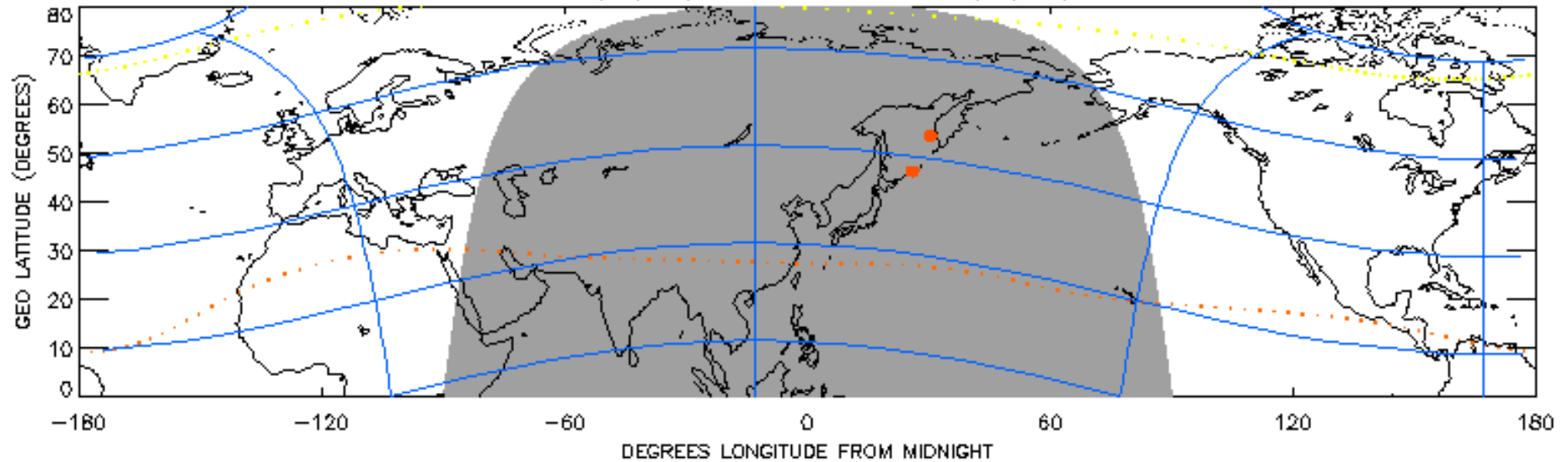
August 28-29, 1859 Event

1859 241 (08/29) 15:00 to 1859 241 (08/29) 15:30



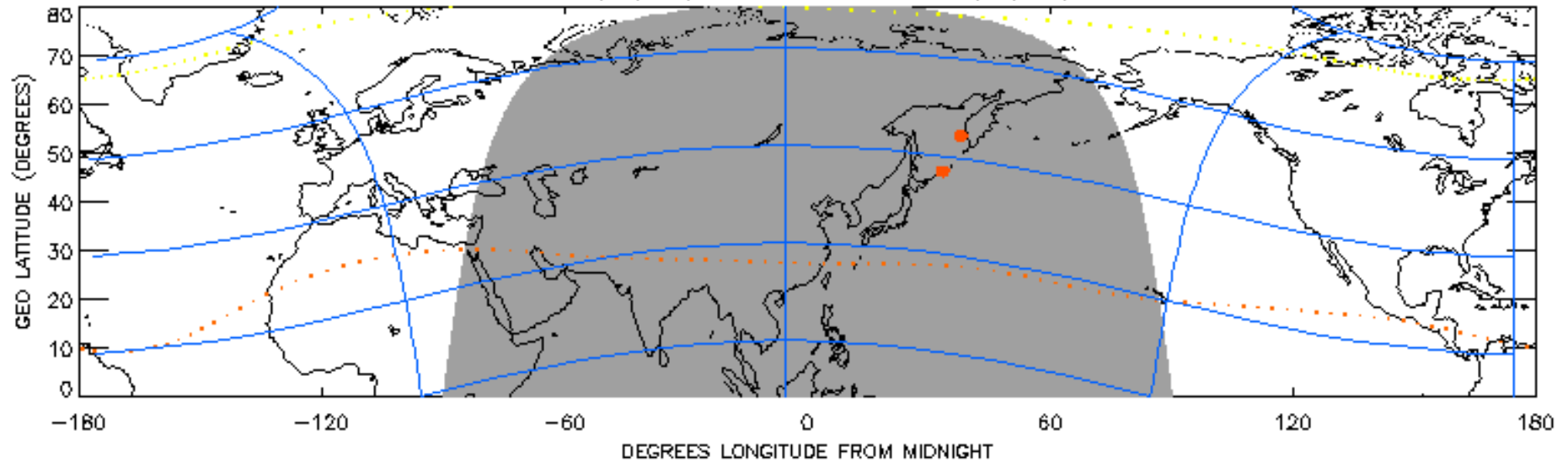
August 28-29, 1859 Event

1859 241 (08/29) 15:30 to 1859 241 (08/29) 16:00

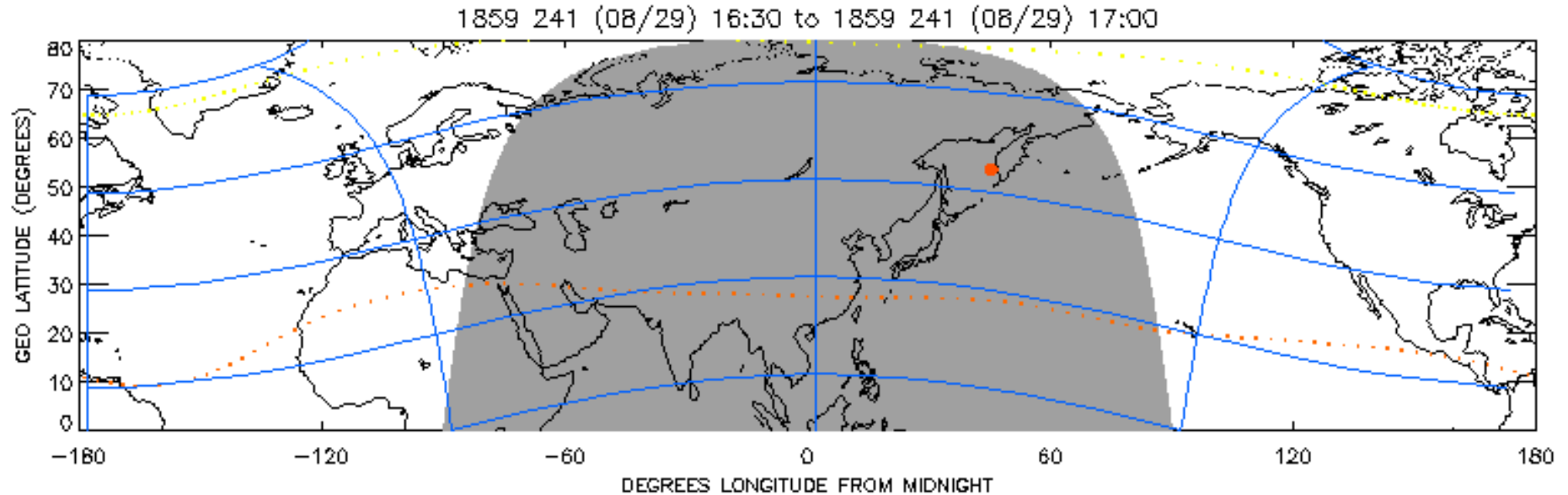


August 28-29, 1859 Event

1859 241 (08/29) 16:00 to 1859 241 (08/29) 16:30

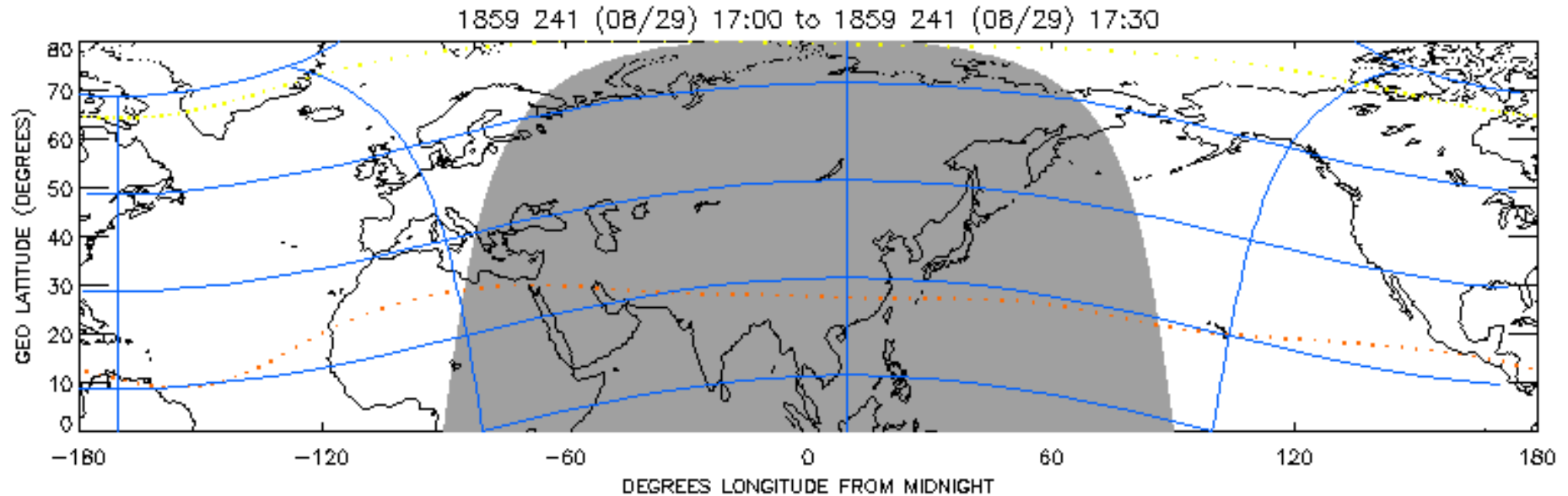


August 28-29, 1859 Event



- Boston Courier - “The aurora borealis is today the chief topic of conversation, and all agree that they have seldom or never witnessed so extensive and remarkable an atmospheric phenomenon.”

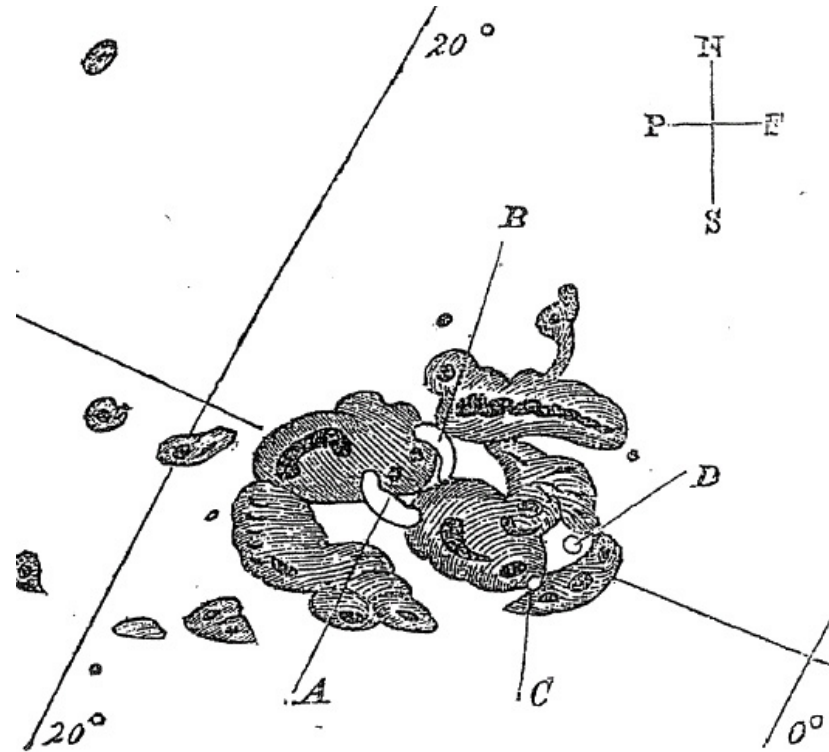
August 28-29, 1859 Event



- Duration of aurora ~19 to 20 hours

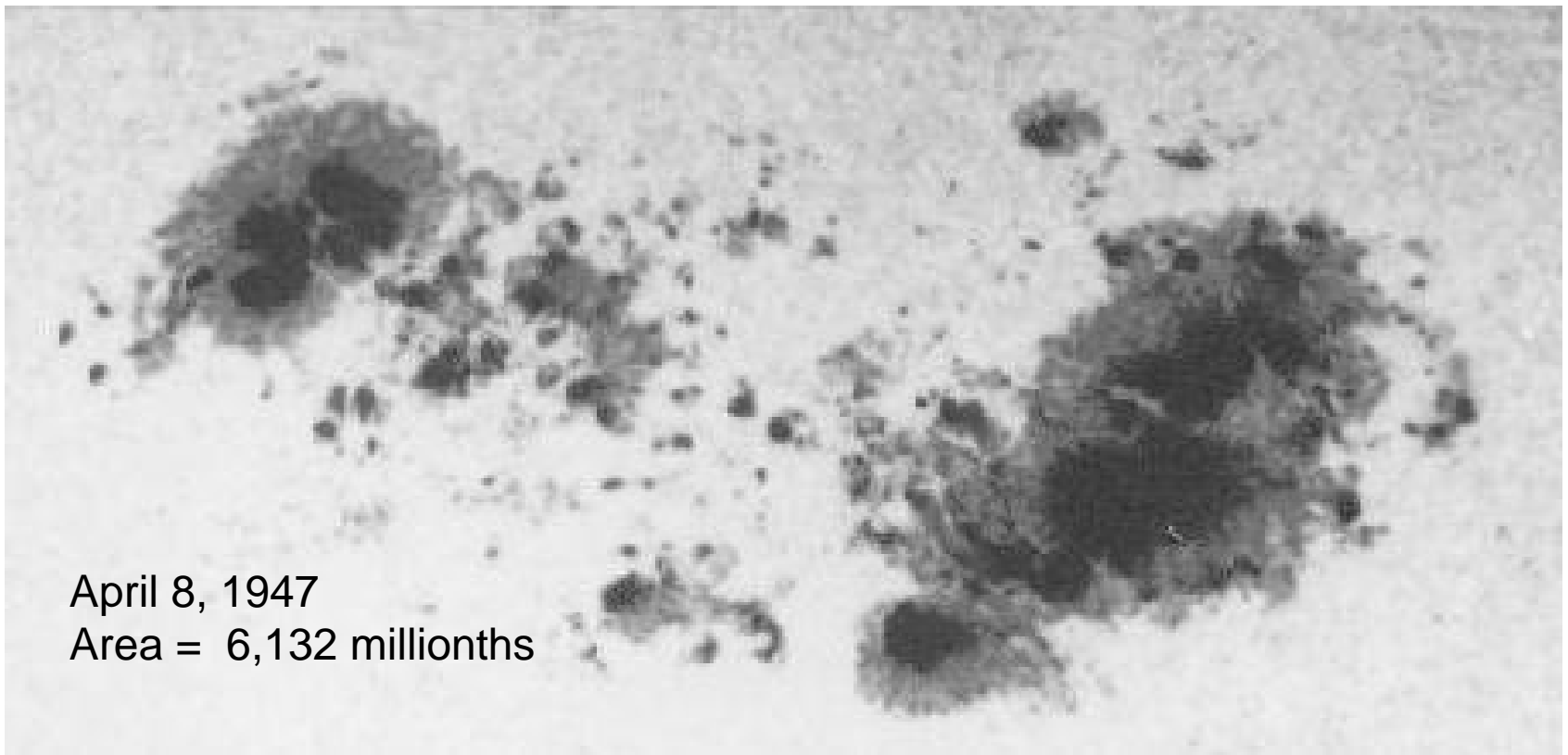
A Massive White Light Flare

- “While engaged in the forenoon [11:18 UT] of Thursday Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. ...two patches of intensely bright and white light broke out, in the positions ...A and B...” Carrington
- Hodgson independently confirmed Carrington’s observations



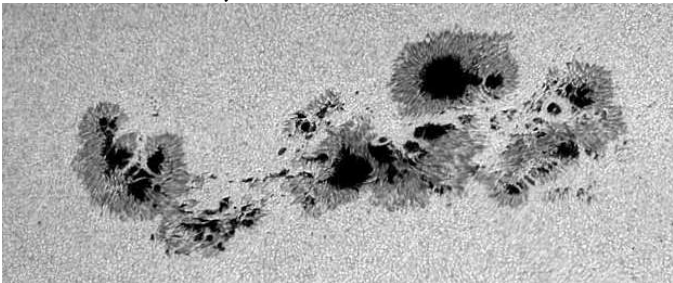
A CME starting at the Photosphere

Carrington, Mon. Not. R. Astron. Soc., 1860
Hodgson, Mon. Not. R. Astron. Soc., 1860

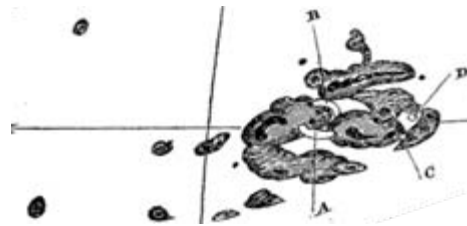


April 8, 1947
Area = 6,132 millionths

September 2000
Area = 2,140 millionths

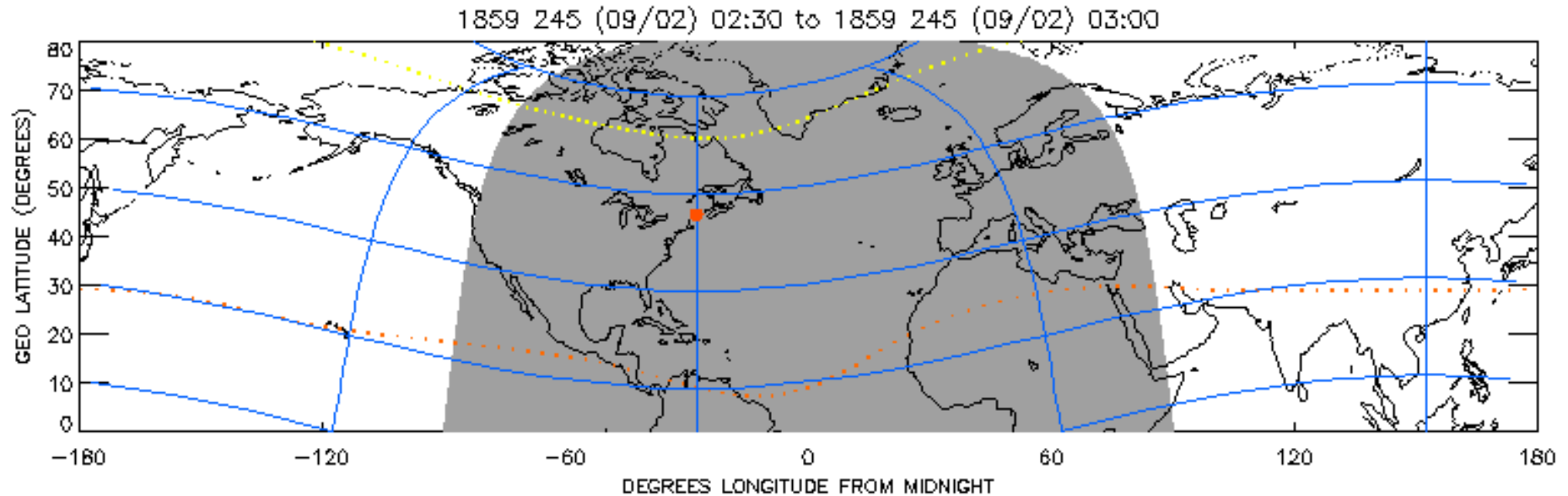


Aug-Sept 1859
Area ~ 1,600 millionths



Note: In the last 15
Solar Cycles this one
Is 10th in sunspot max

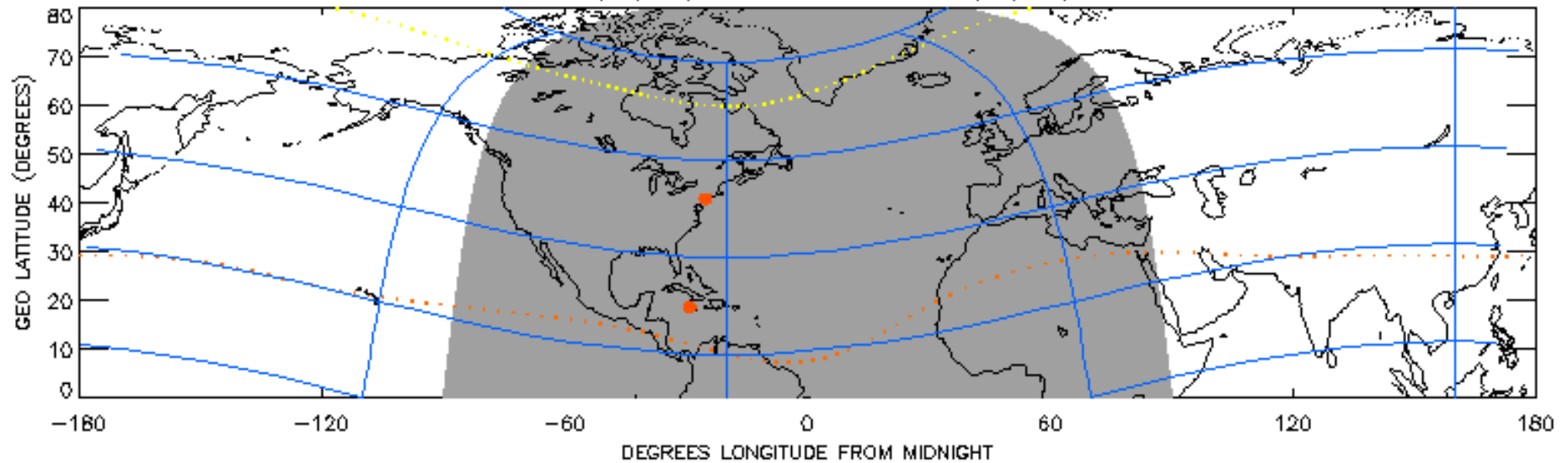
September 2, 1859 Event



- Time since Carrington-Hodgson flare ~17 hours
- August 28/29 ICME probably “cleared” a path to Earth accounting for the rapid time for the coronal material to reach the Earth’s magnetosphere

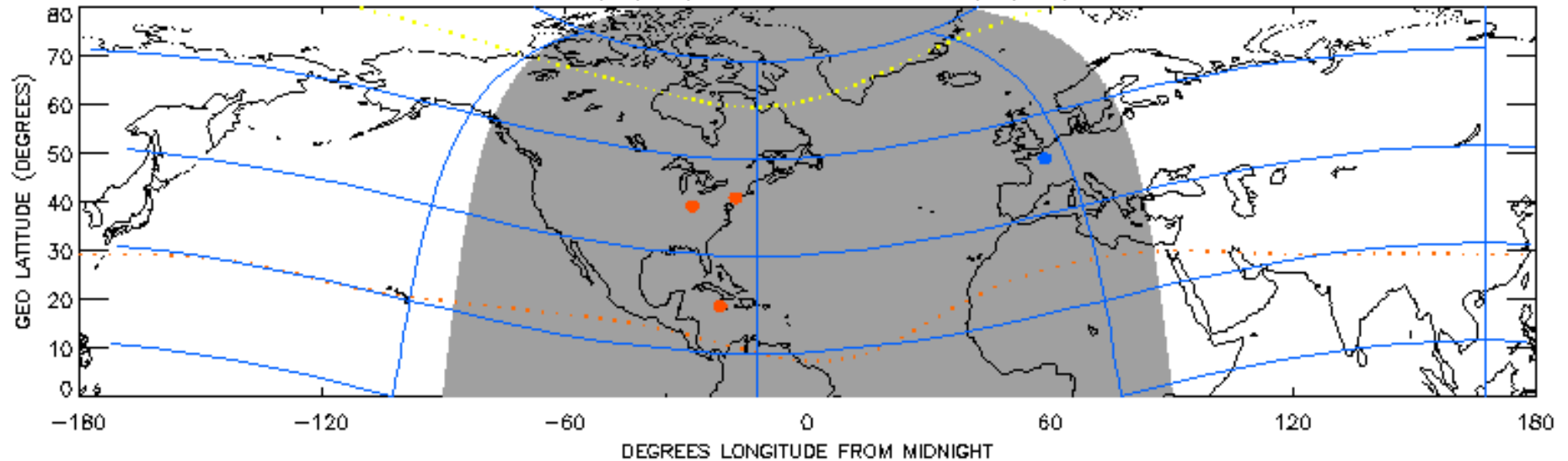
September 2, 1859 Event

1859 245 (09/02) 03:00 to 1859 245 (09/02) 03:30



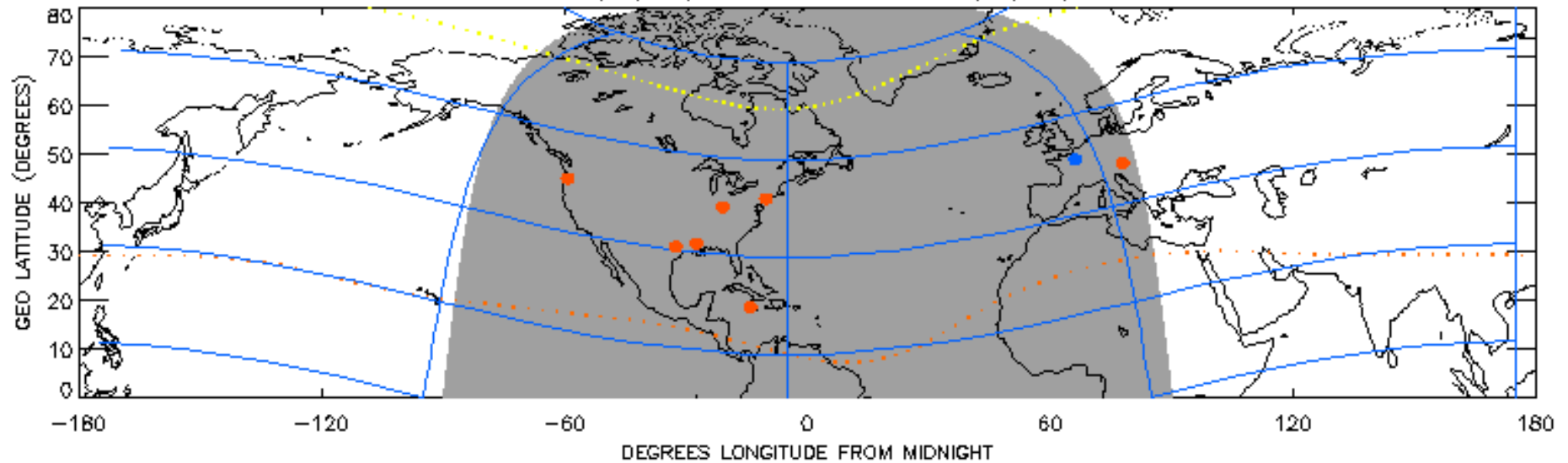
September 2, 1859 Event

1859 245 (09/02) 03:30 to 1859 245 (09/02) 04:00

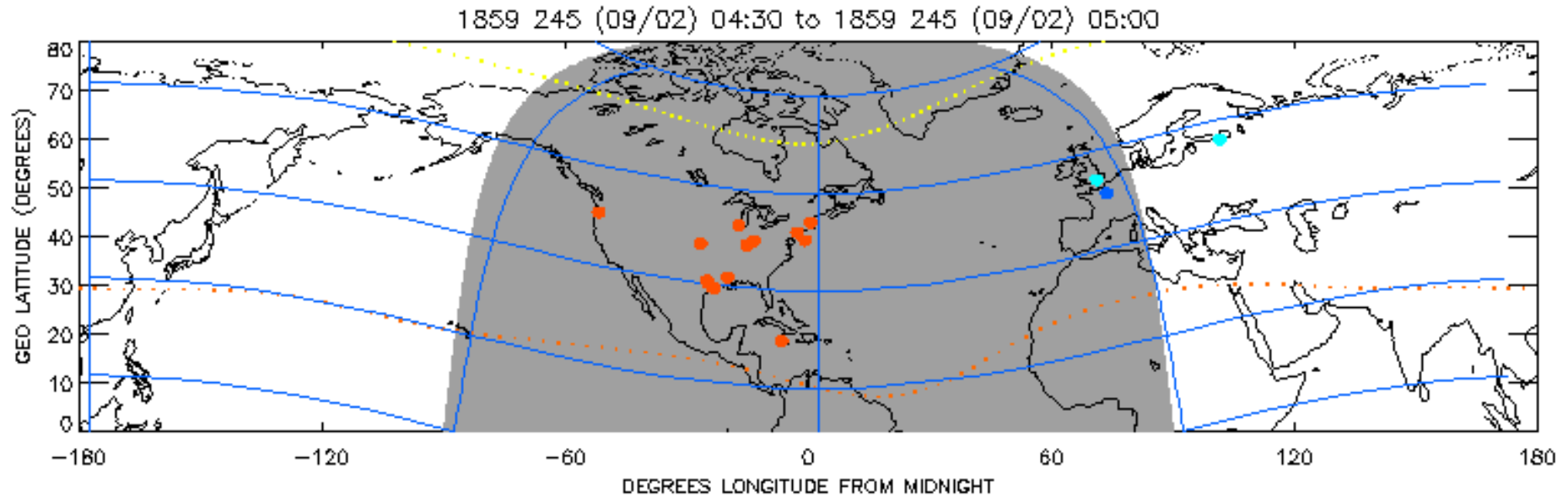


September 2, 1859 Event

1859 245 (09/02) 04:00 to 1859 245 (09/02) 04:30



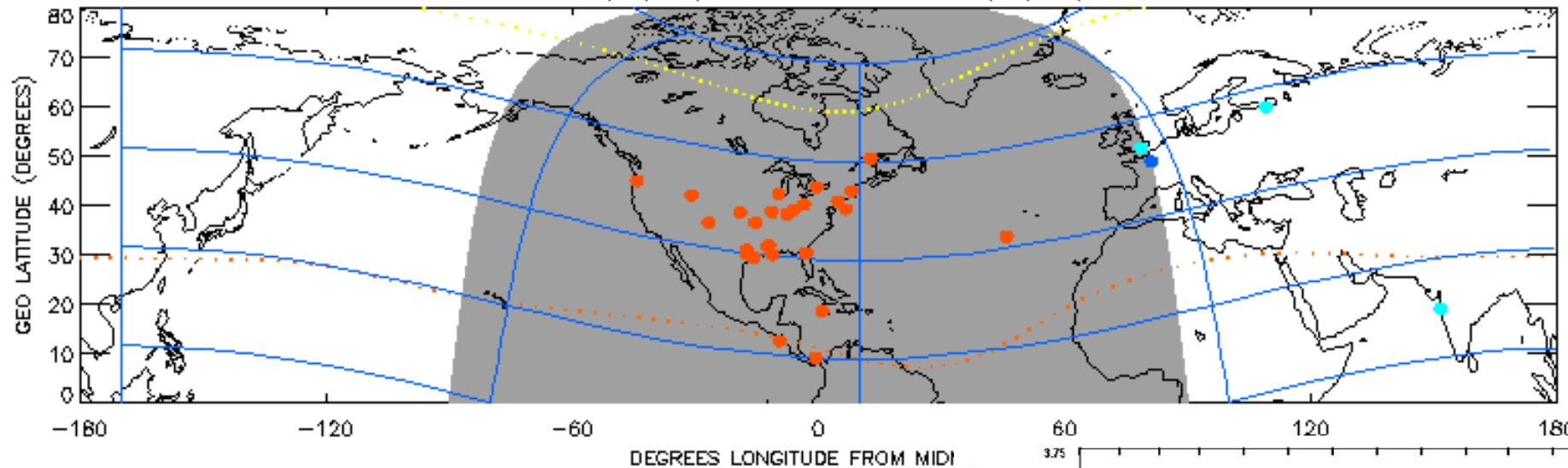
September 2, 1859 Event



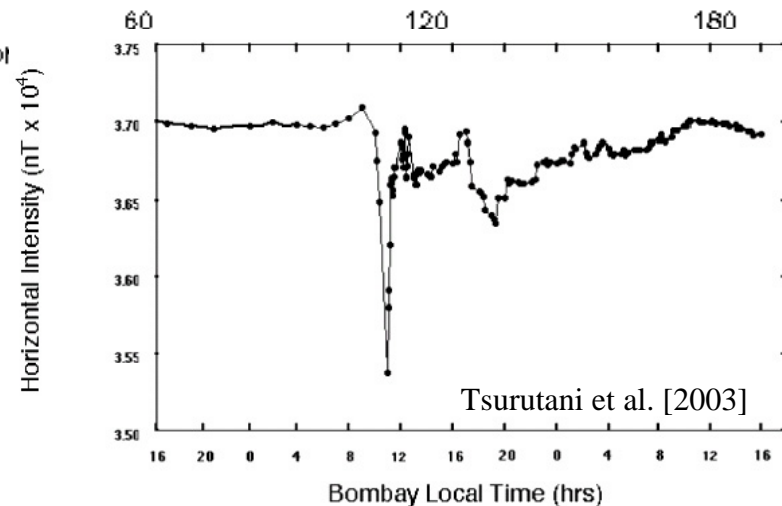
- Rochester NY - “Some who saw the display attributed it to fires in the towns about.”

September 2, 1859 Event

1859 245 (09/02) 05:00 to 1859 245 (09/02) 05:30



- Bombay, India magnetometer observations of -1760 nT
 - Ring Current (Tsurutani et al.) ?
 - Or is it the auroral electrojet, magnetopause currents or all of them?

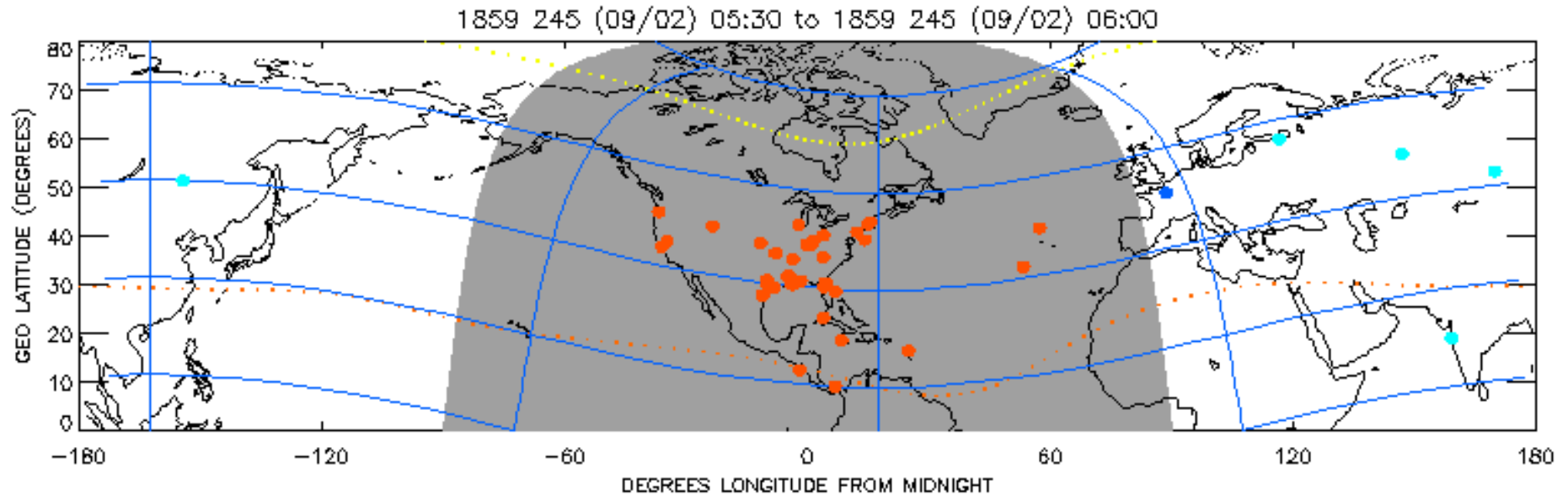


Sept. 1

Sept. 2

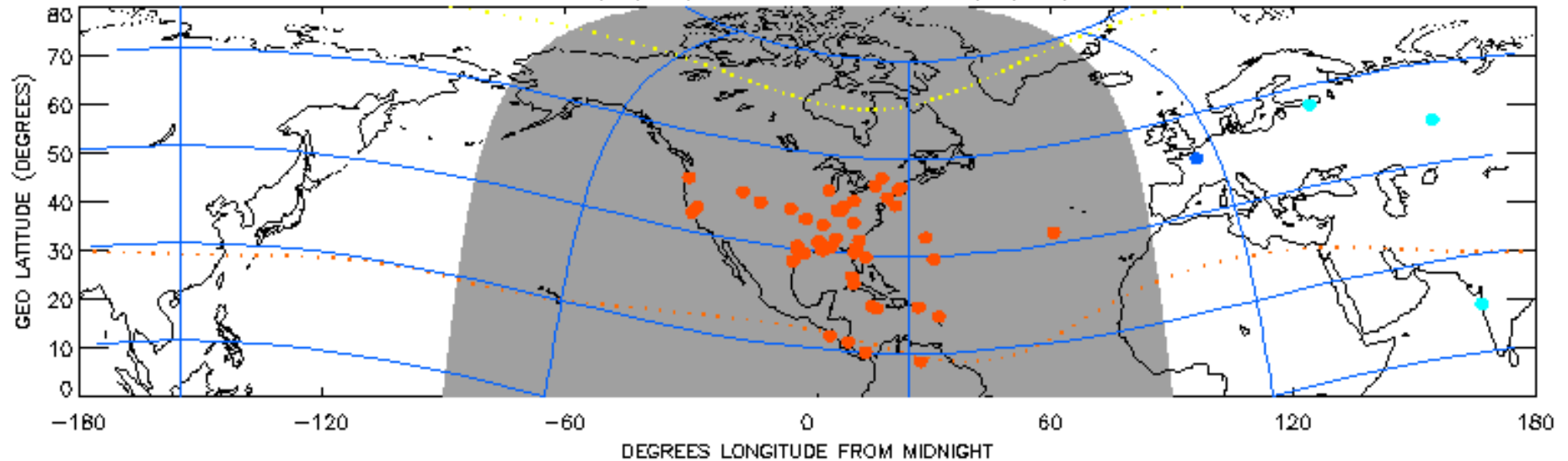
Sept. 3

September 2, 1859 Event

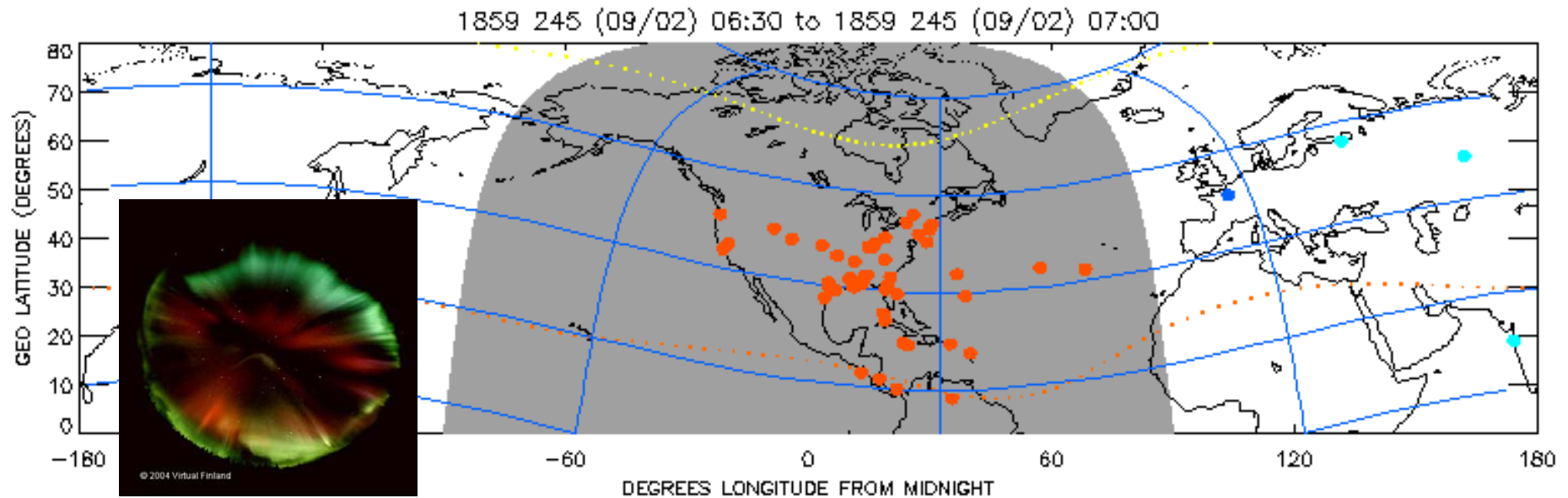


September 2, 1859 Event

1859 245 (09/02) 06:00 to 1859 245 (09/02) 06:30

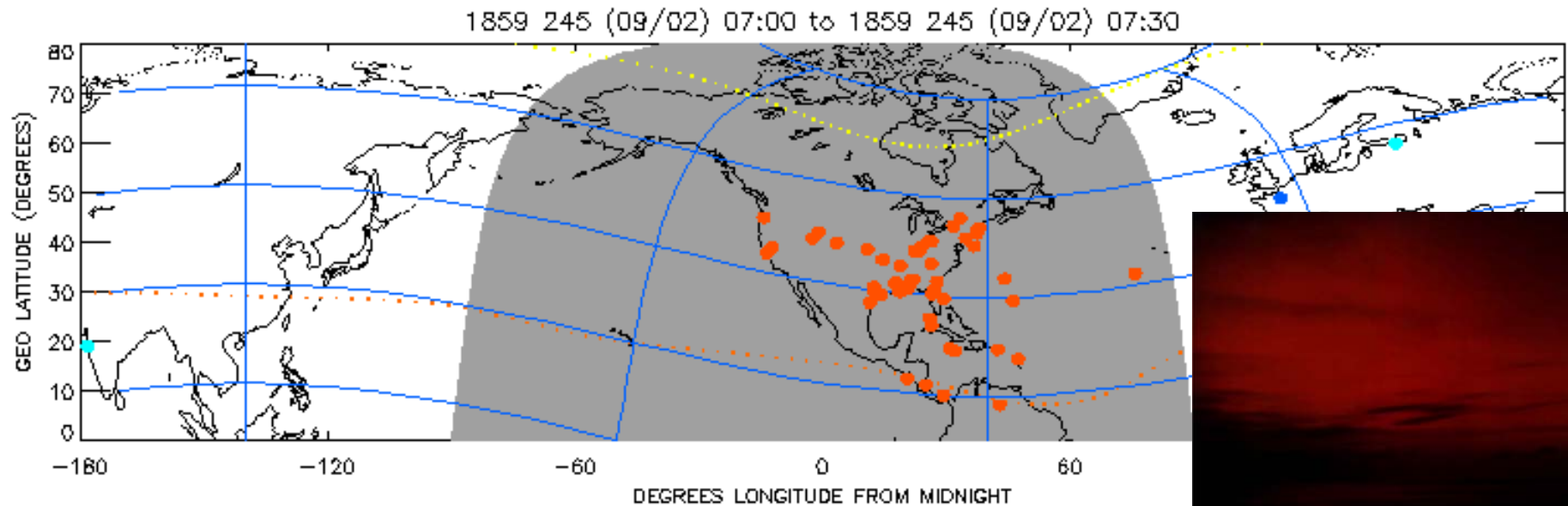


September 2, 1859 Event



- Messenger (deck log: Lat. 49°) “we witnessed the most magnificent display of the aurora boreales (sic) imaginable ... the whole firmament was a blaze of Crimson shooting up from all points of the compass but the most splendid from the South W. I have not the language to describe it”

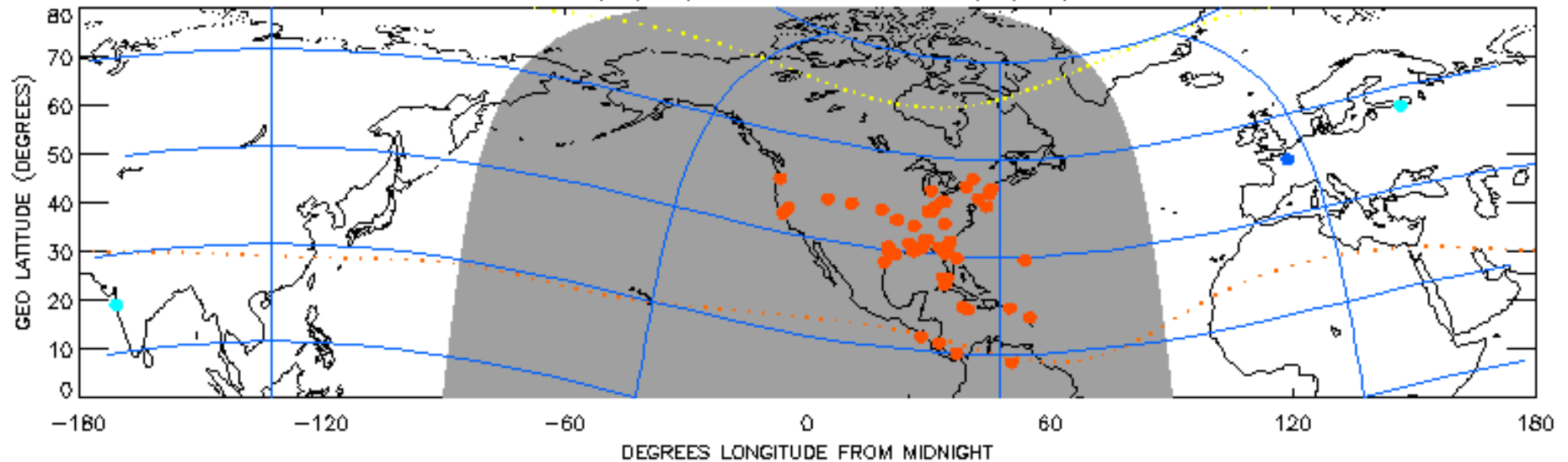
September 2, 1859 Event



- NY Times - “the heavens were a livid red flame...”
- New Orleans Daily - “ordinary print could be read by its light...”

September 2, 1859 Event

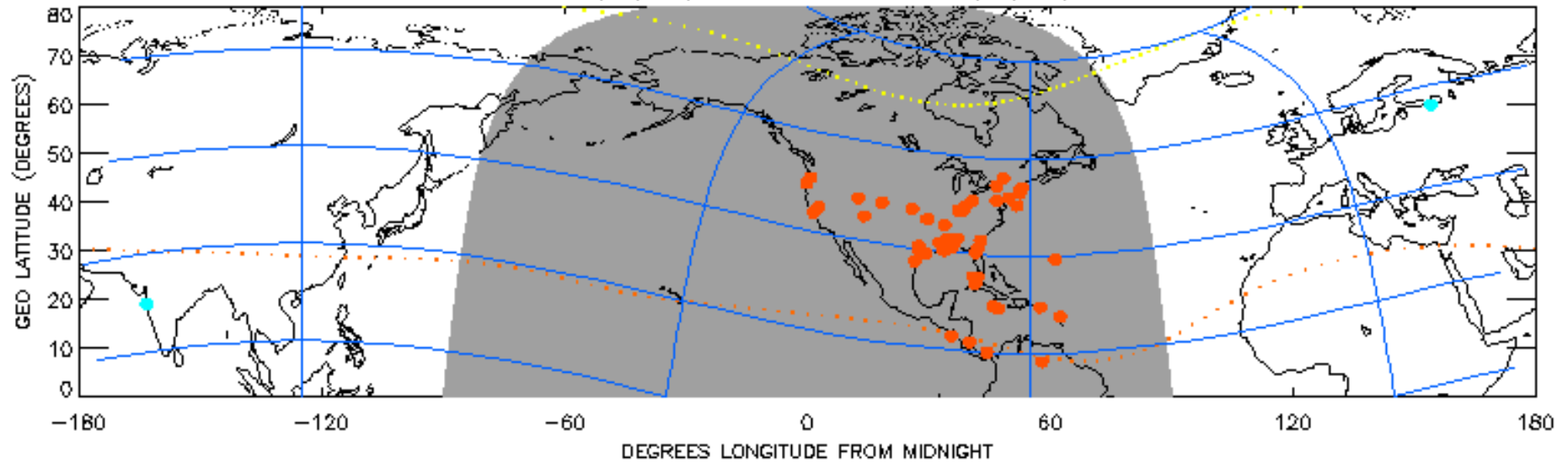
1859 245 (09/02) 07:30 to 1859 245 (09/02) 08:00



- Rocky Mt. Globe - “the red appearance in the sky ... which we first supposed was the reflection from a fire...~11:30 it began to assume the appearance of day breaking and in an hour was almost as light as day, the stars, which before shown brightly being invisible...”

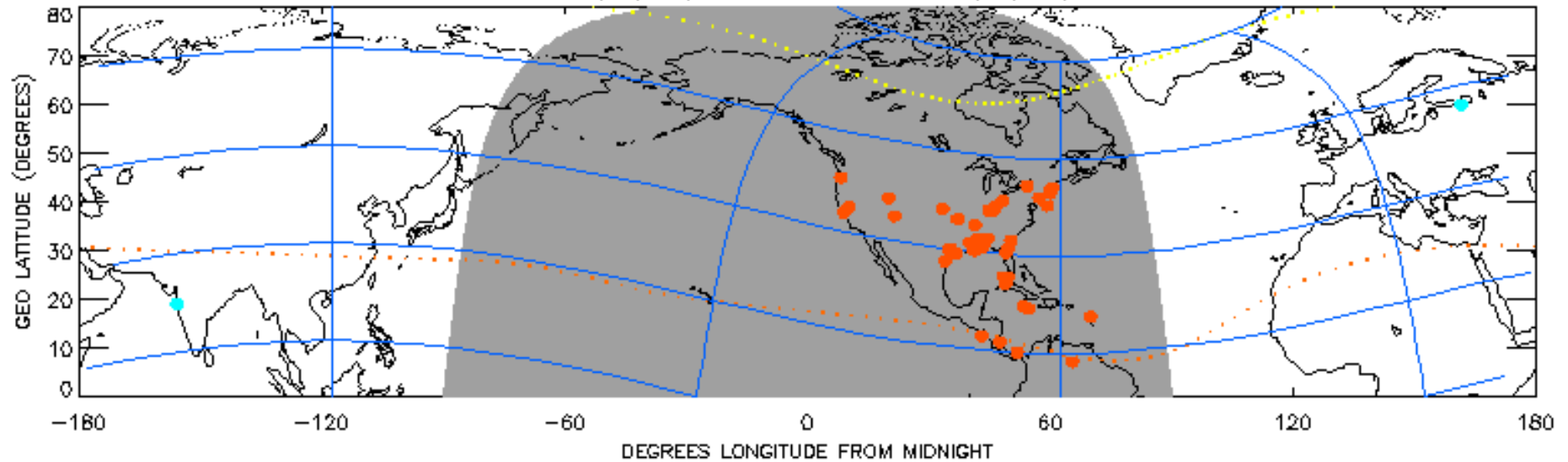
September 2, 1859 Event

1859 245 (09/02) 08:00 to 1859 245 (09/02) 08:30

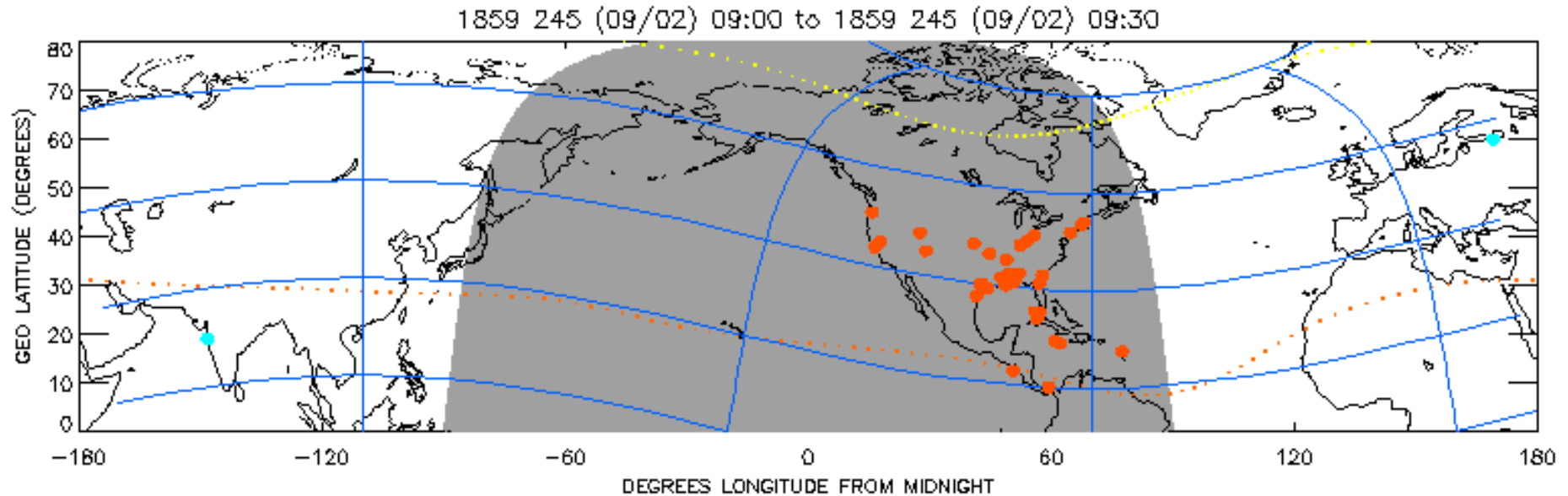


September 2, 1859 Event

1859 245 (09/02) 08:30 to 1859 245 (09/02) 09:00



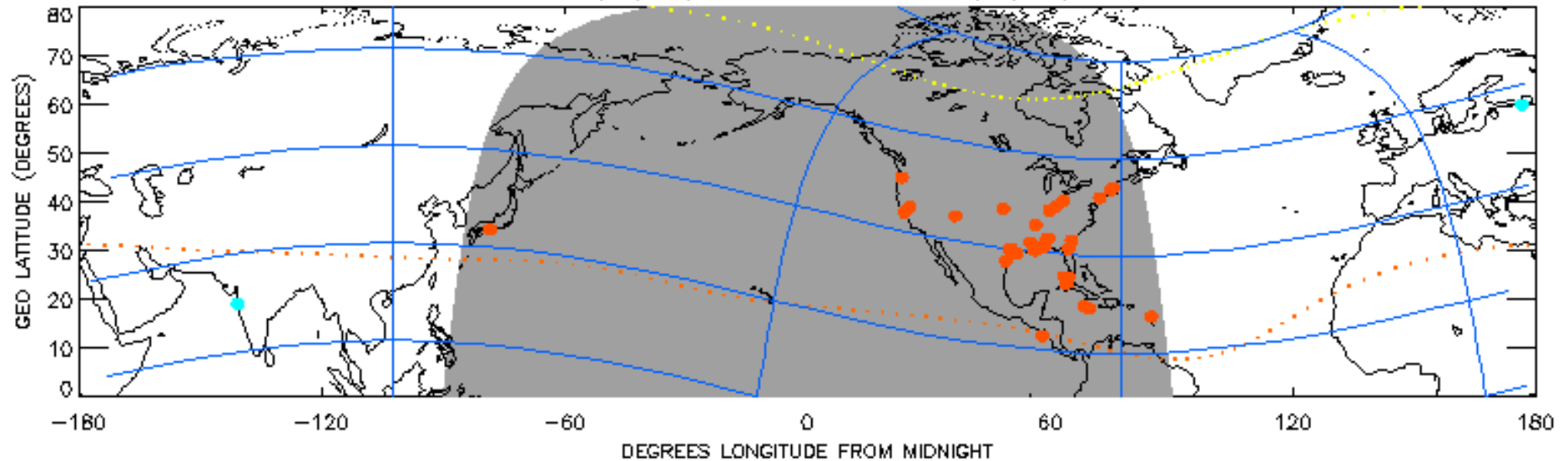
September 2, 1859 Event



- New York Times - “...it was chiefly confined to the southern heavens [south of NY], and hence was more properly an *Aurora Australis* than an *Aurora Borealis*”

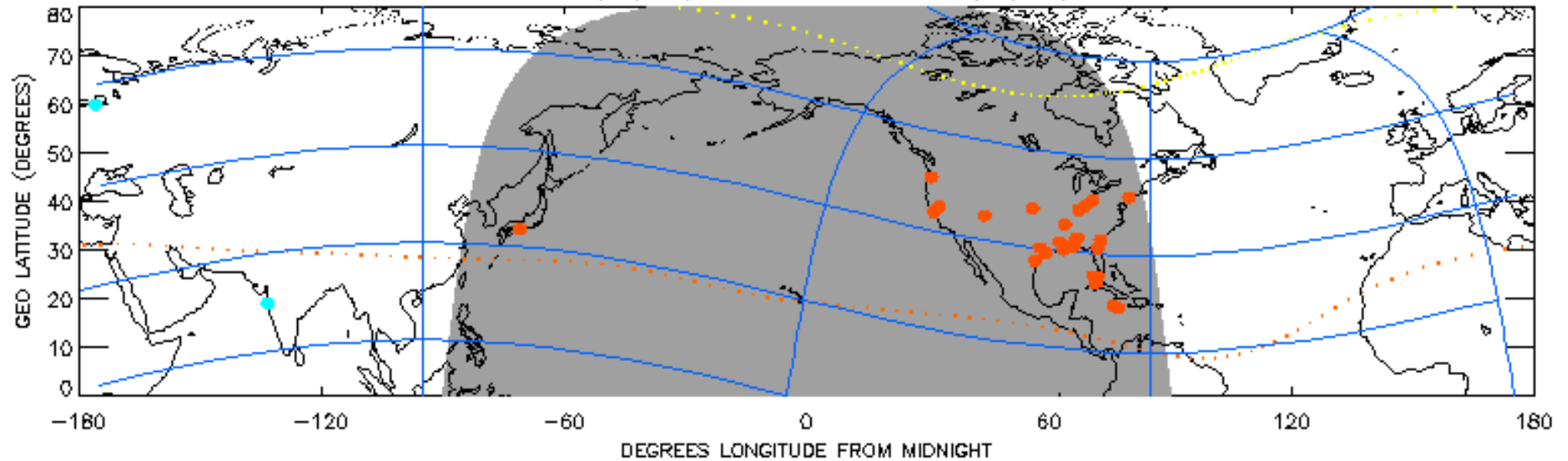
September 2, 1859 Event

1859 245 (09/02) 09:30 to 1859 245 (09/02) 10:00

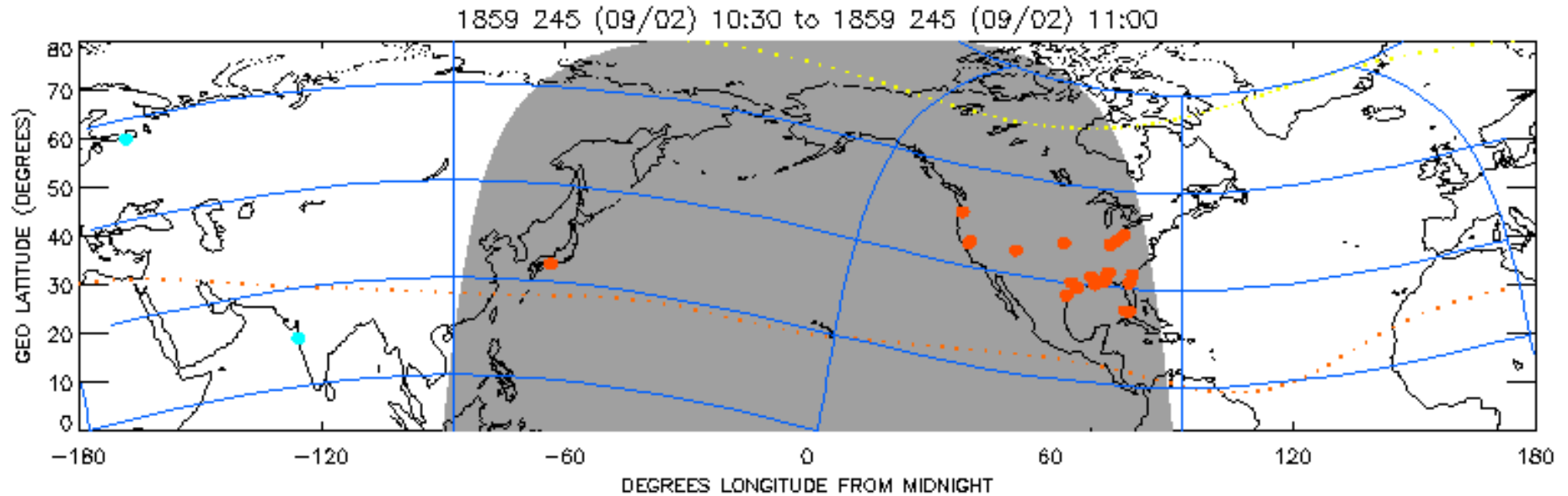


September 2, 1859 Event

1859 245 (09/02) 10:00 to 1859 245 (09/02) 10:30

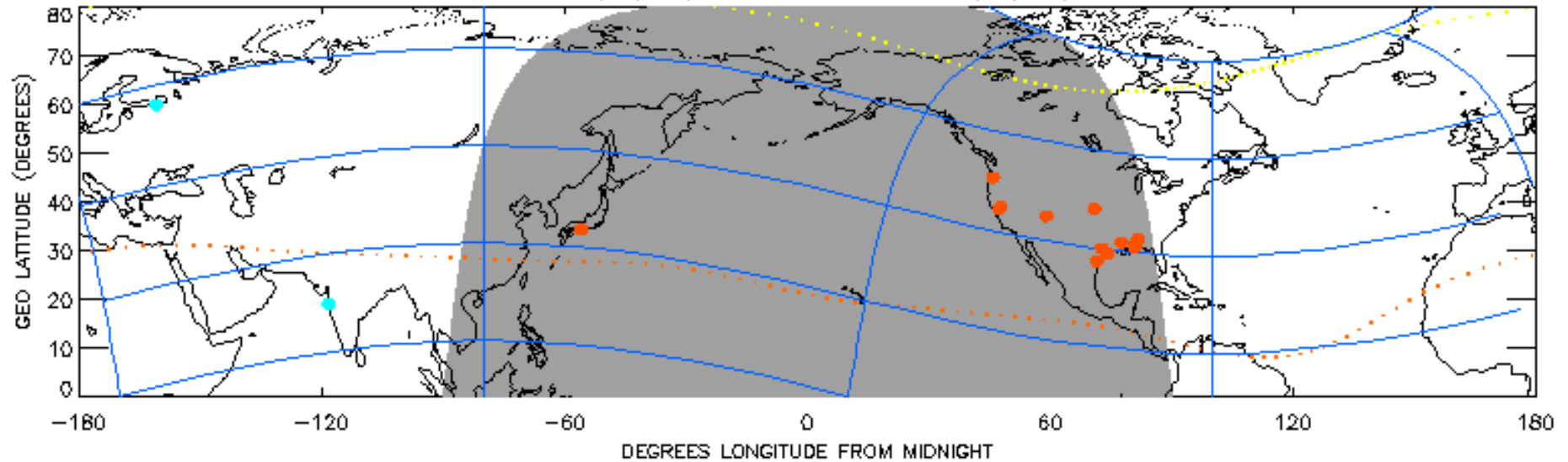


September 2, 1859 Event

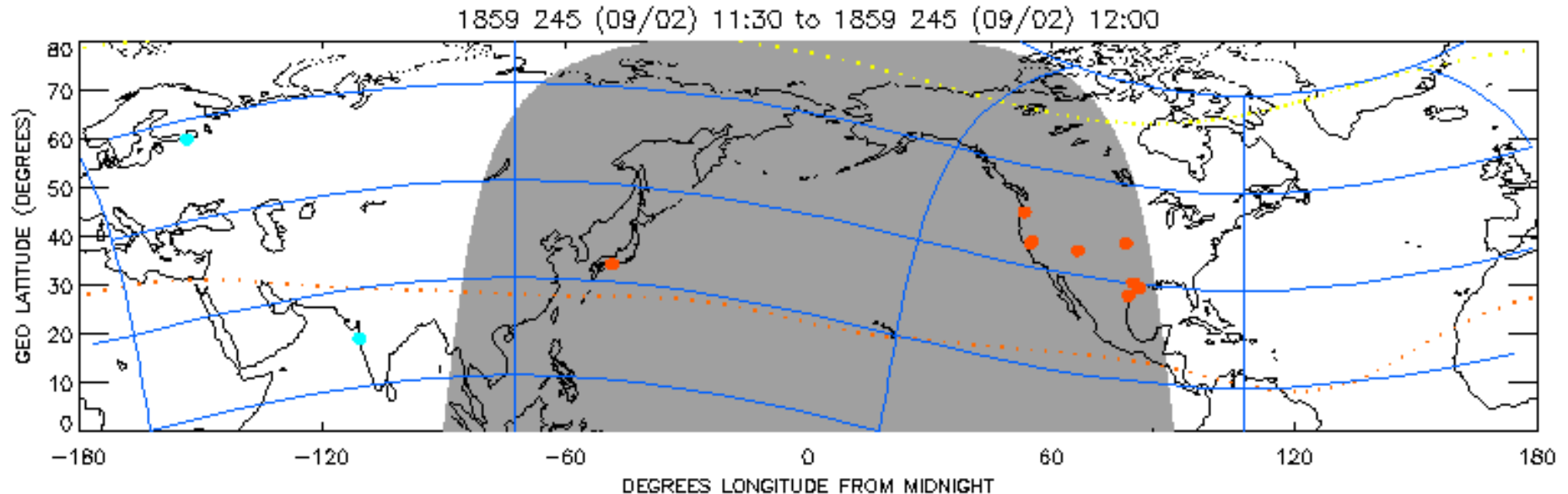


September 2, 1859 Event

1859 245 (09/02) 11:00 to 1859 245 (09/02) 11:30

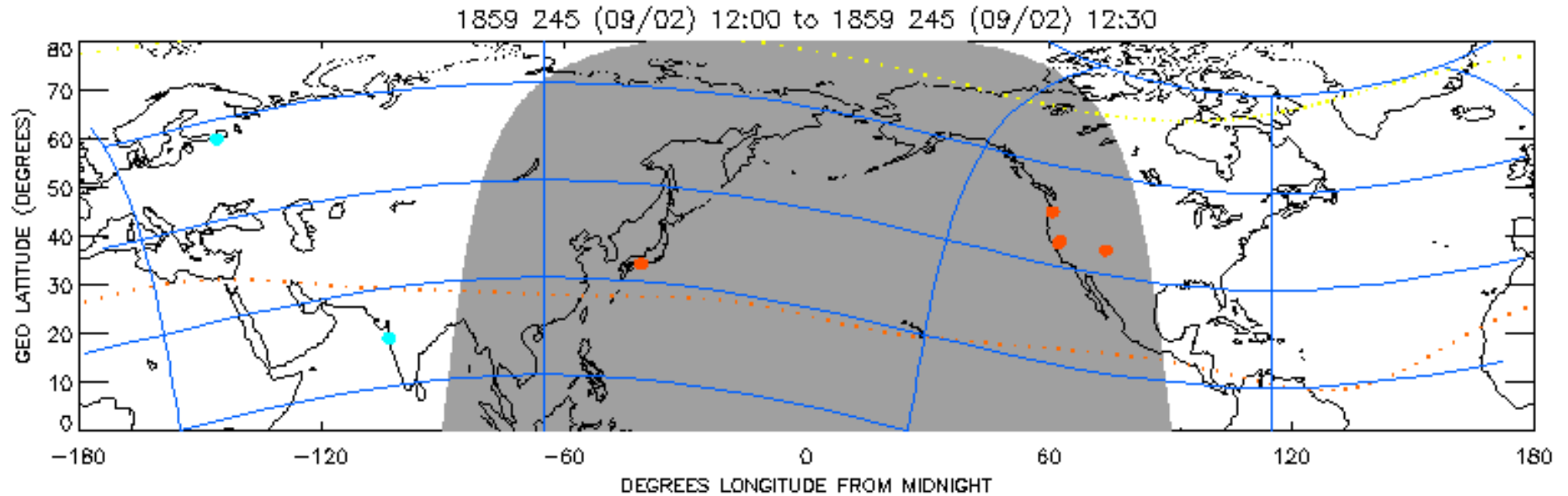


September 2, 1859 Event



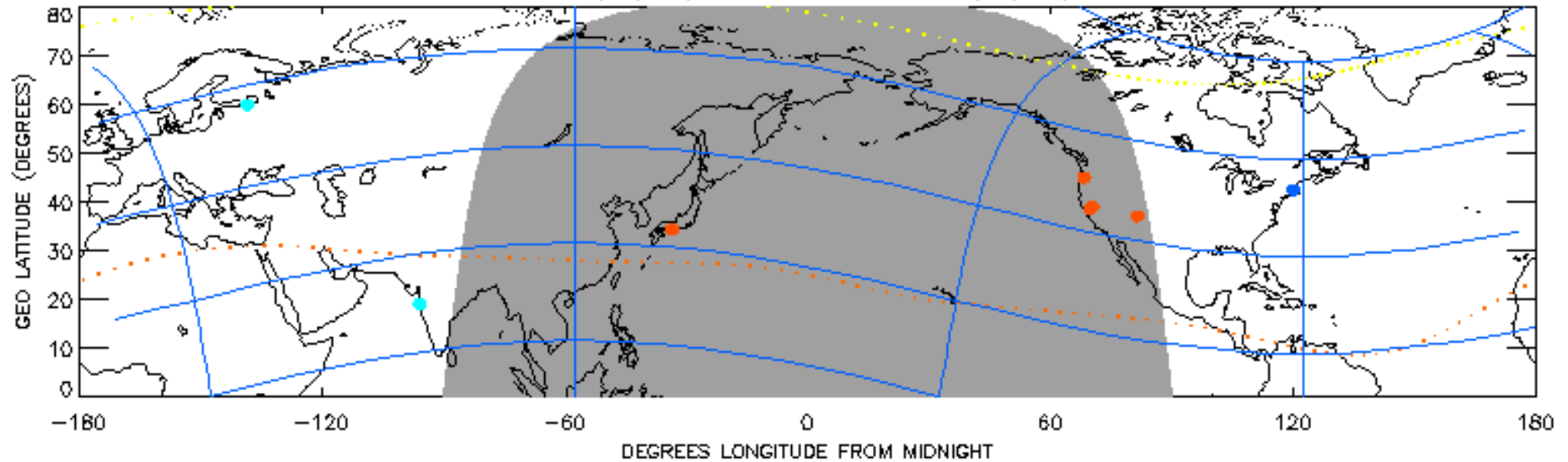
- Cincinnati Daily - “The auroral currents were sufficiently powerful ... to enable the telegraphic operators at Portland to transmit messages to Boston without resorting to the use of the batteries: and similar phenomena were observed at Pittsburgh.”
- “Who now will dispute the theory that the Aurora Borealis is caused by electricity?”

September 2, 1859 Event



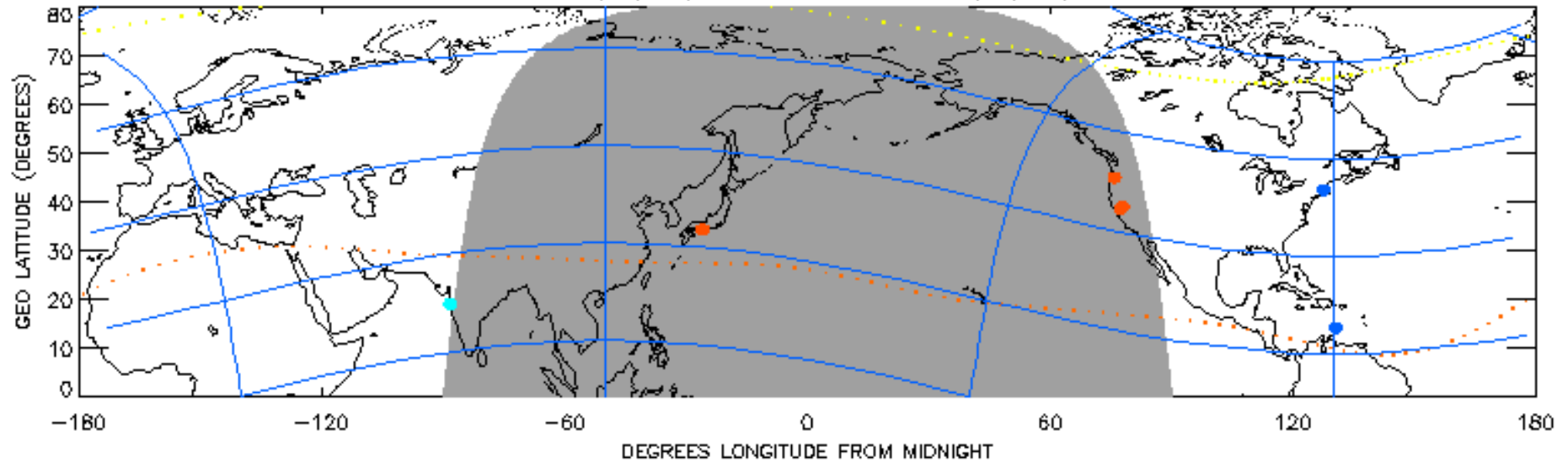
September 2, 1859 Event

1859 245 (09/02) 12:30 to 1859 245 (09/02) 13:00



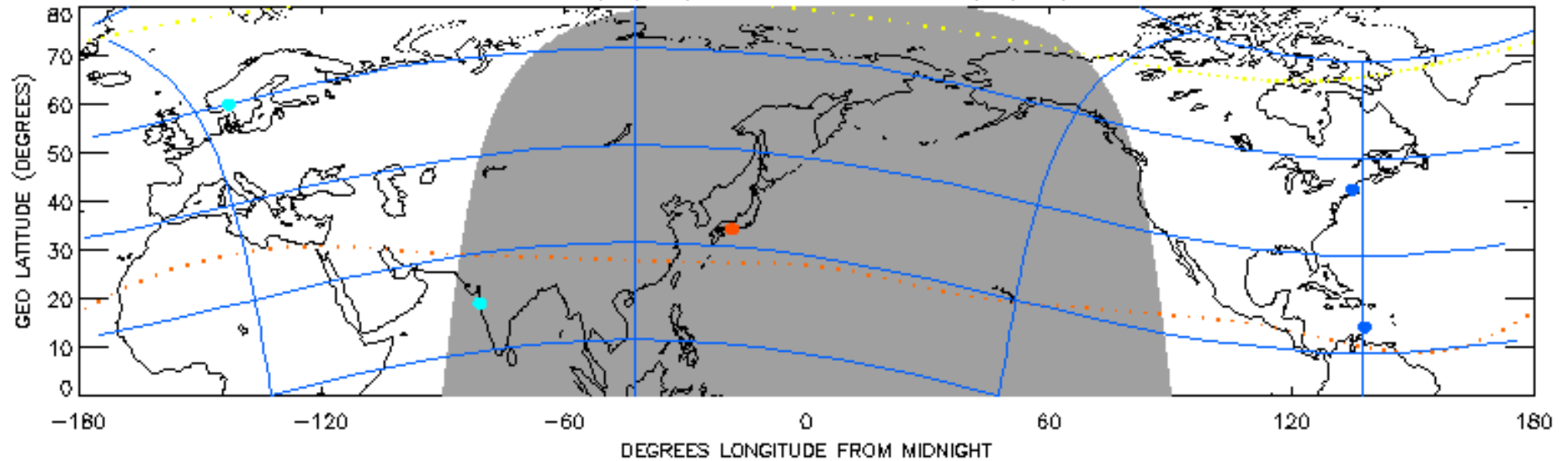
September 2, 1859 Event

1859 245 (09/02) 13:00 to 1859 245 (09/02) 13:30



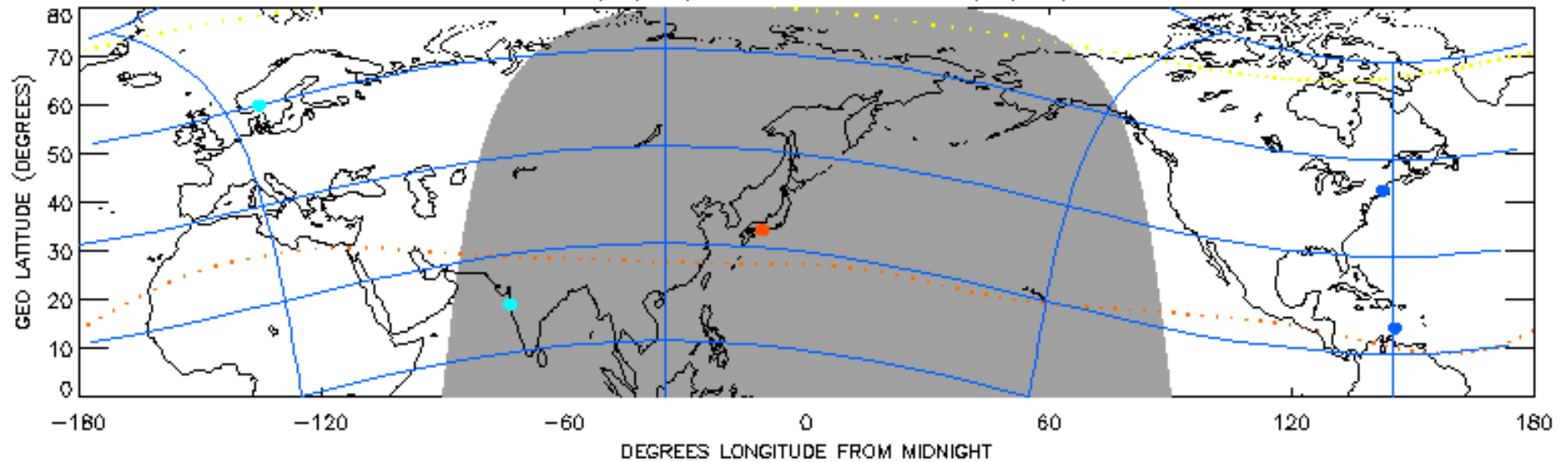
September 2, 1859 Event

1859 245 (09/02) 13:30 to 1859 245 (09/02) 14:00



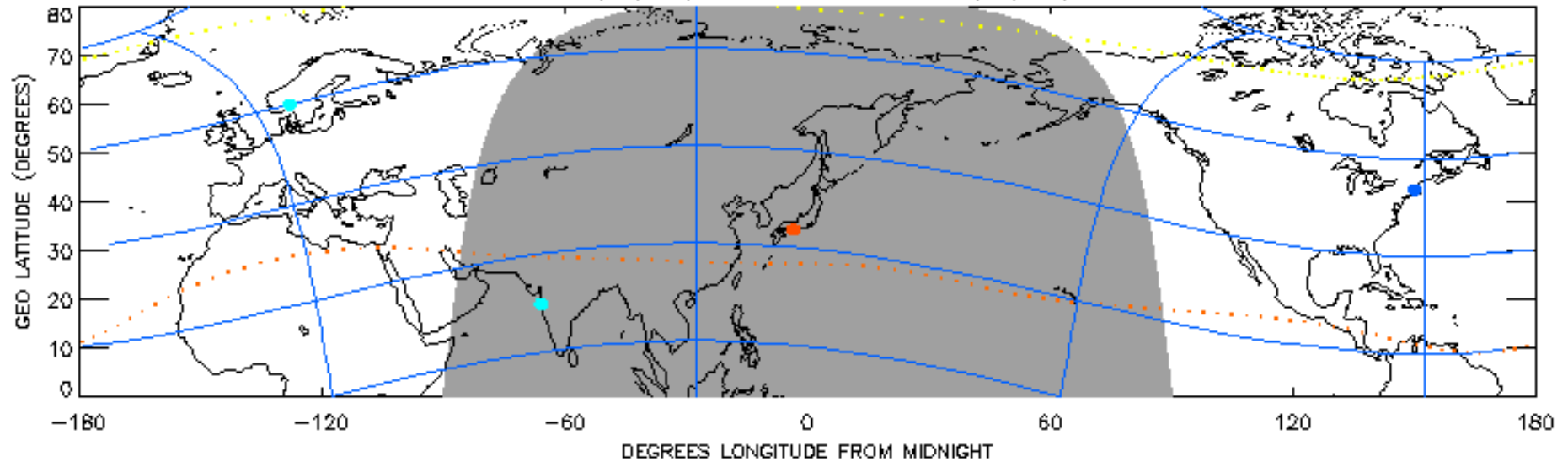
September 2, 1859 Event

1859 245 (09/02) 14:00 to 1859 245 (09/02) 14:30



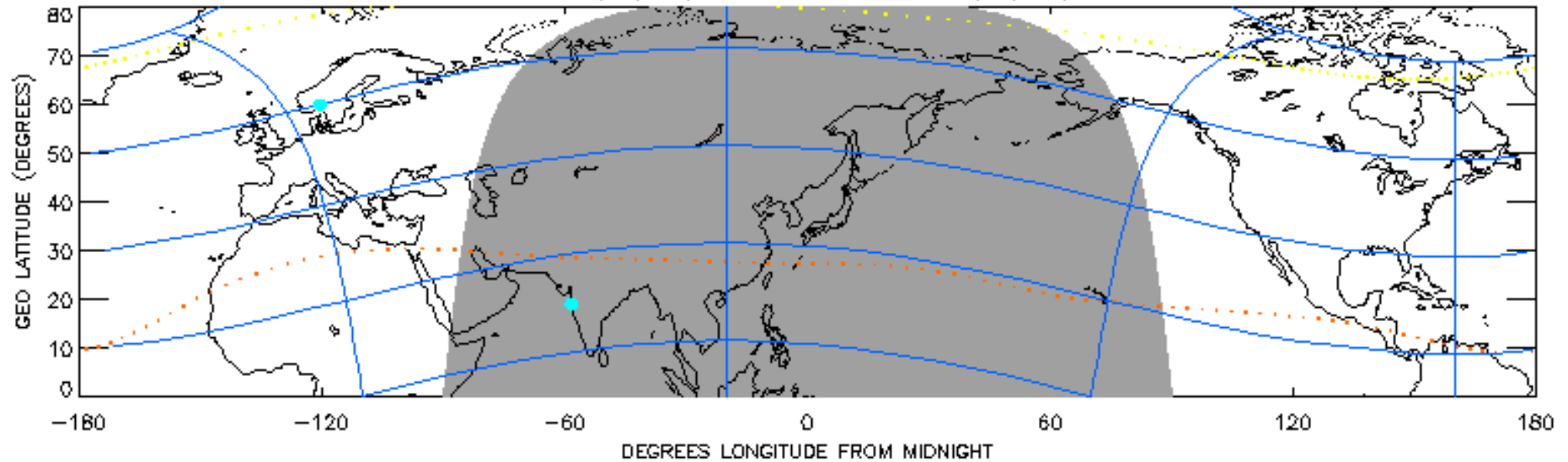
September 2, 1859 Event

1859 245 (09/02) 14:30 to 1859 245 (09/02) 15:00



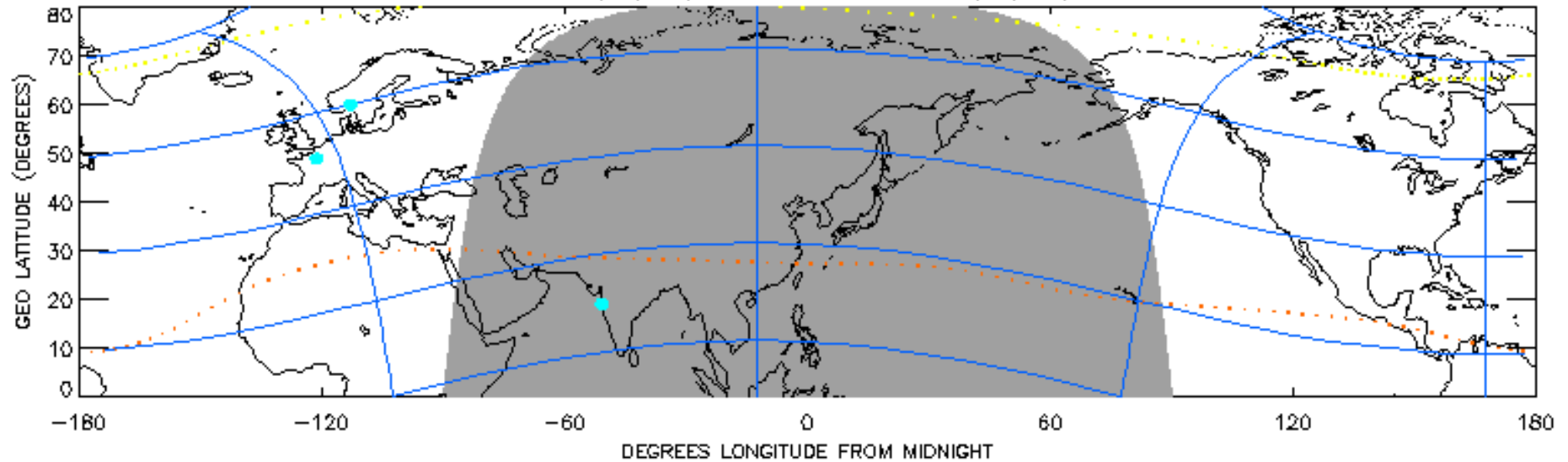
September 2, 1859 Event

1859 245 (09/02) 15:00 to 1859 245 (09/02) 15:30



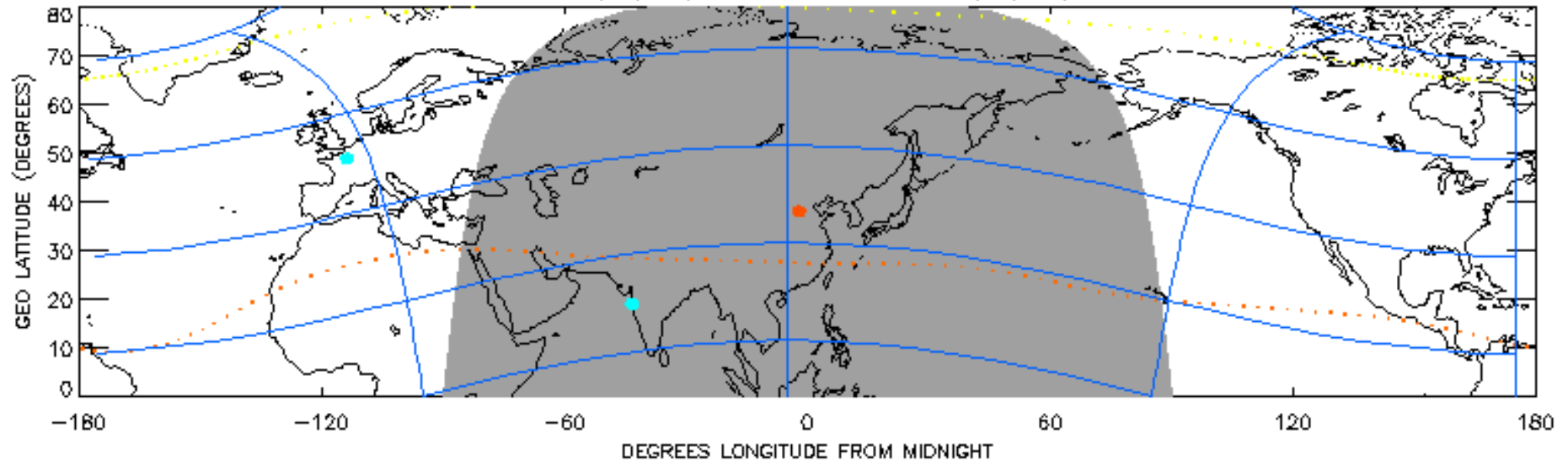
September 2, 1859 Event

1859 245 (09/02) 15:30 to 1859 245 (09/02) 16:00



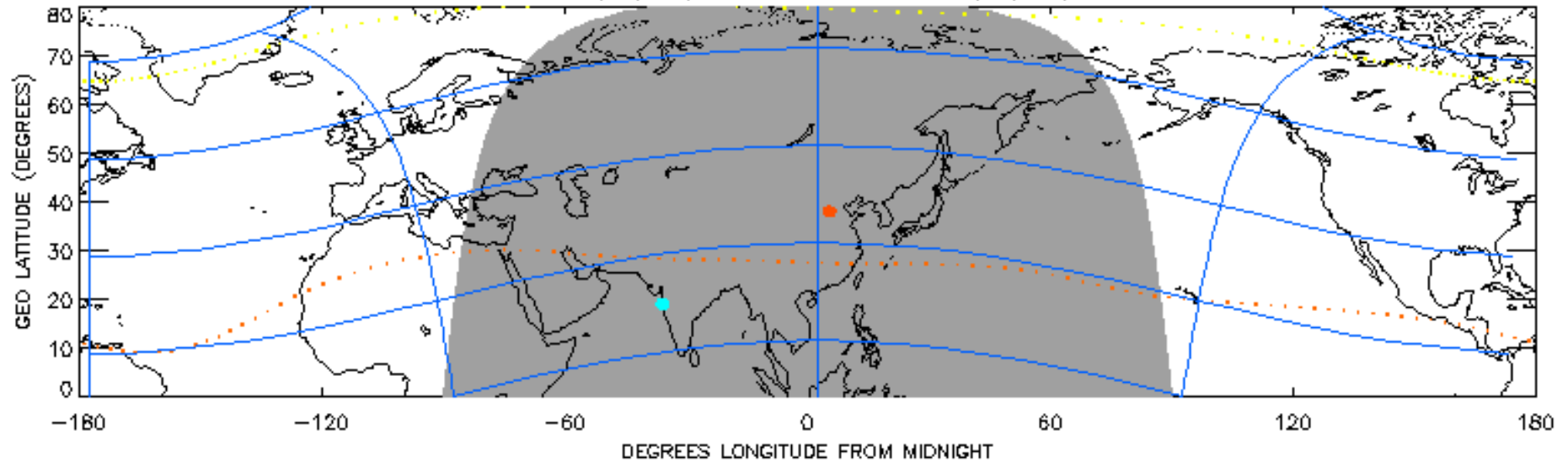
September 2, 1859 Event

1859 245 (09/02) 16:00 to 1859 245 (09/02) 16:30



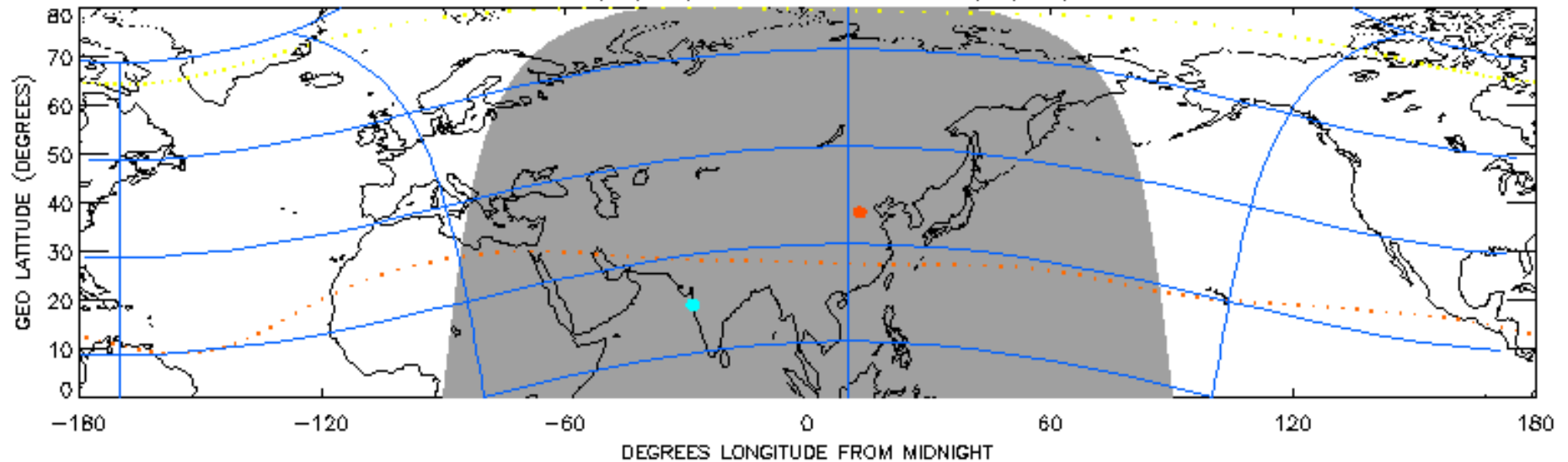
September 2, 1859 Event

1859 245 (09/02) 16:30 to 1859 245 (09/02) 17:00

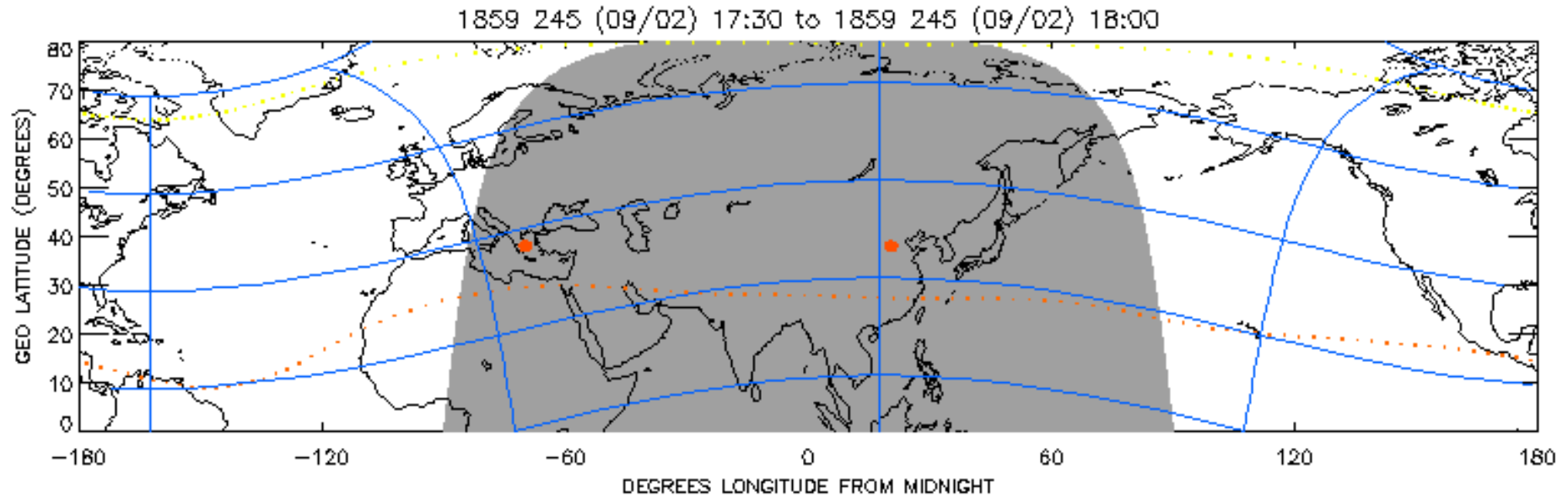


September 2, 1859 Event

1859 245 (09/02) 17:00 to 1859 245 (09/02) 17:30

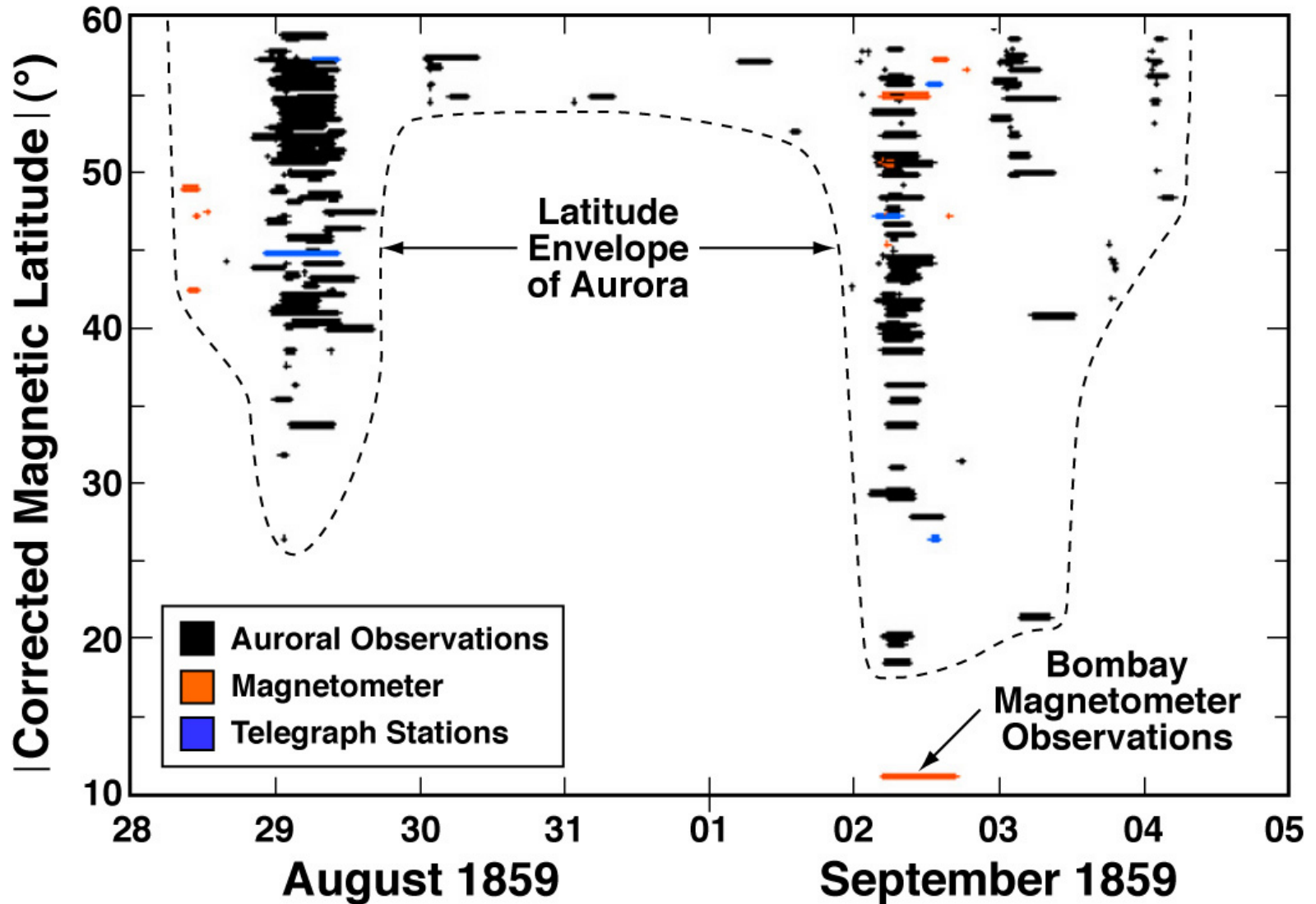


September 2, 1859 Event



- Duration of the aurora continues for more than 24 hrs
- Many sources stated that this auroral event was even brighter than the August 28-29th event

Latitudinal Extent



Overview of the 1859 Event

- Combination of conditions aided the large number of eyewitness reports
 - New moon (partial solar eclipse) occurred on Aug. 28th
 - US was largely free of clouds
 - Telegraphs, the communications marvel of their time, all over the world were effected
- The aurora reached extremely low geomagnetic latitudes (corrected to 1900) on August 28-29 ($\sim 25^\circ$) and on September 2 ($\sim 18^\circ$)
- Auroral forms of all types and colors were observed for ~ 20 hours on Aug. 28-29 and ~ 24 hours on Sept 2
 - A brilliant Type A red aurora was visible for several hours in both events. Bright enough to read by!
- The Aug.- Sept. 1859 event is the granddaddy of events in the last 150 years - the top superstorm
 - Seminal event that put more scientists on the right track!

Backup

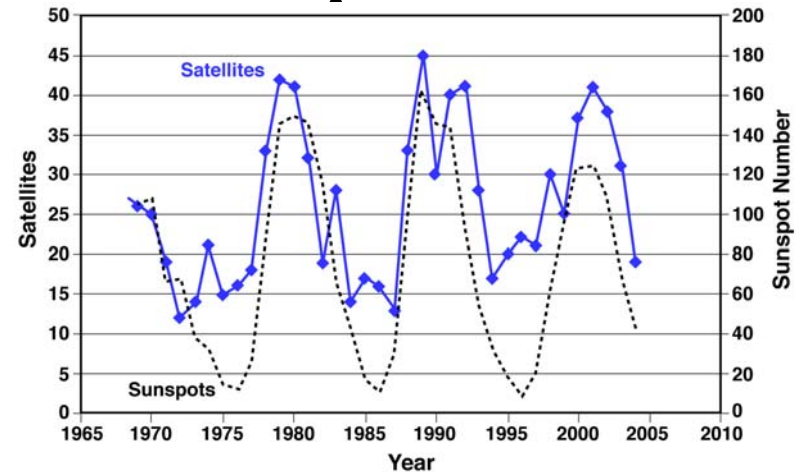
The Economic Real Estate

Location	Commercial	Military	Research	Total
LEO	273	94	70	437
MEO	19	101	12	132
GEO	308	51	8	367
Totals:	600	245	91	936

- Total Satellite Fleet (ca Dec, 2004)..... ~ 936
- Total hardware + launch cost..... ~ \$ 230 billion
- GEO Transponder Capacity..... ~ 6,800
- GEO industry annual revenue..... \$ 87 billion
- LEO + MEO satellite annual revenue..... \$ 10 billion
- Satellite Industry annual revenue..... \$ 225 billion

Potential Economic Impacts

- LEO - increased drag
 - Modeling needed
- GEO - Communications
 - Modeling industry transponder usage and planned degradation with time
 - Solar power degradation from SPE effects of 1859 magnitude
 - Effects not modeled - operator/engineer limitations by dealing with a large number of simultaneous anomalies and local charging effects
 - Best estimate is about \$30B
 - Mitigating effects include: regular replacement, diversity of vendors, newer solar cell materials (from Si to GaAS/Ge)



Other large economic events...

San Francisco Earthquake.....1906.....\$ 500 billion

Hurricane Katrina.....2005.....\$ 120 billion

Annual loss from electricity interruptions.....\$ 80 billion

North American Power Grid Blackout.....\$ 30 billion/day

GEO satellite revenue loss.....\$ >25 billion

Blackout of East Coast.....1965.....\$ 10 billion

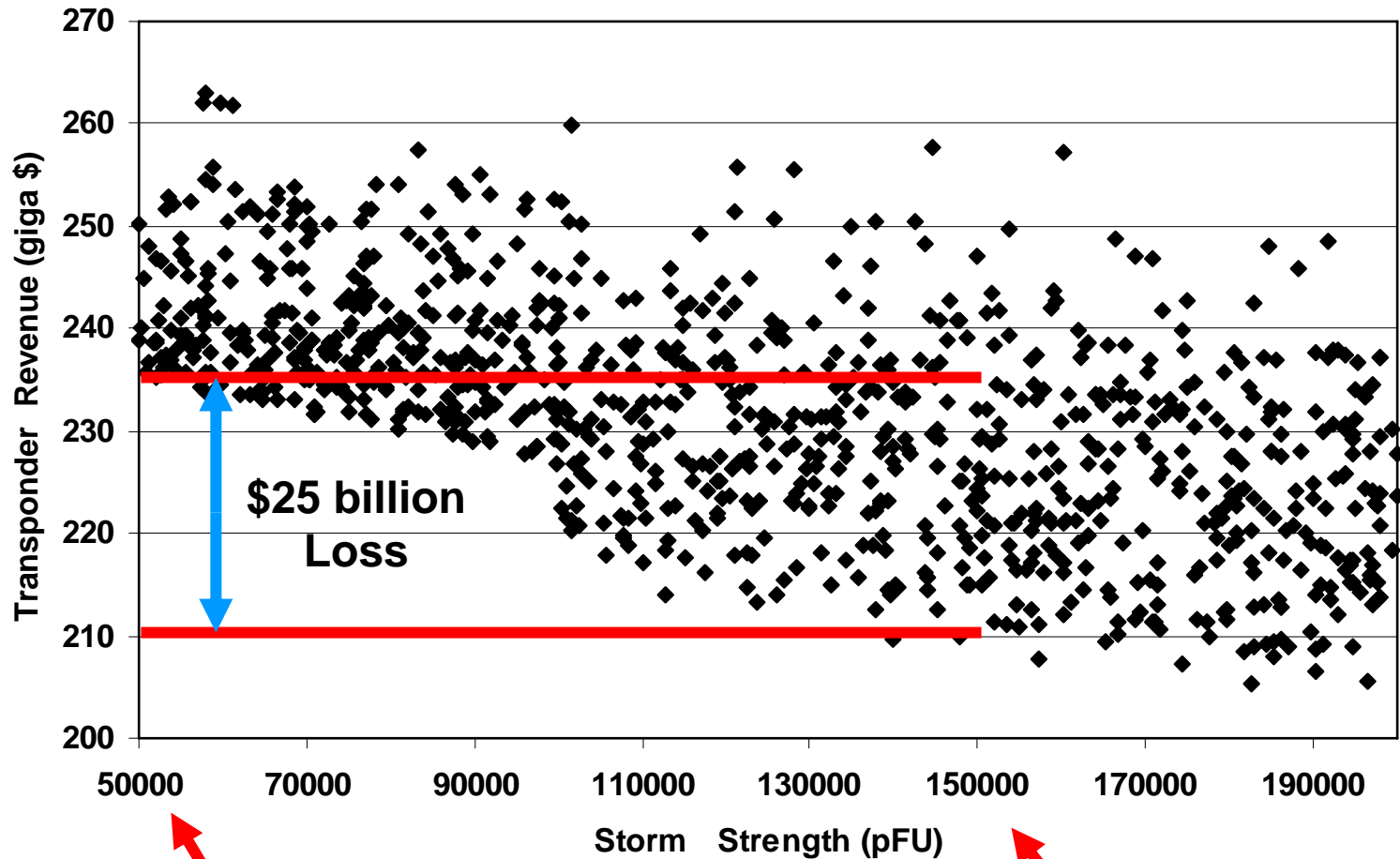
Mt Lassen Volcanic Eruption...1915.....\$ 5 billion

Quebec Blackout.....1989.....\$ 2 billion

SOHO SPE events and power declines

Date	Power Decline	Proton Flux (pfu) >10 MeV	Fluence 10 MeV (10⁹ /cm²)
July 14, 2000	2 %	24,000	11.5
November 6, 2001	2 %	31,700	15.0
November 9, 2000	1.5 %	14,800	9.1
September 25, 2001	1 %	12,900	7.4
October 29, 2003	1.7%	29,500	~14.0

Monte Carlo simulation of cumulative transponder revenue versus storm strength.



40,000 pfu = 10/19/1989
43,000 pfu = 3/23/1991

4 x 'worst case'

A simple satellite economic model

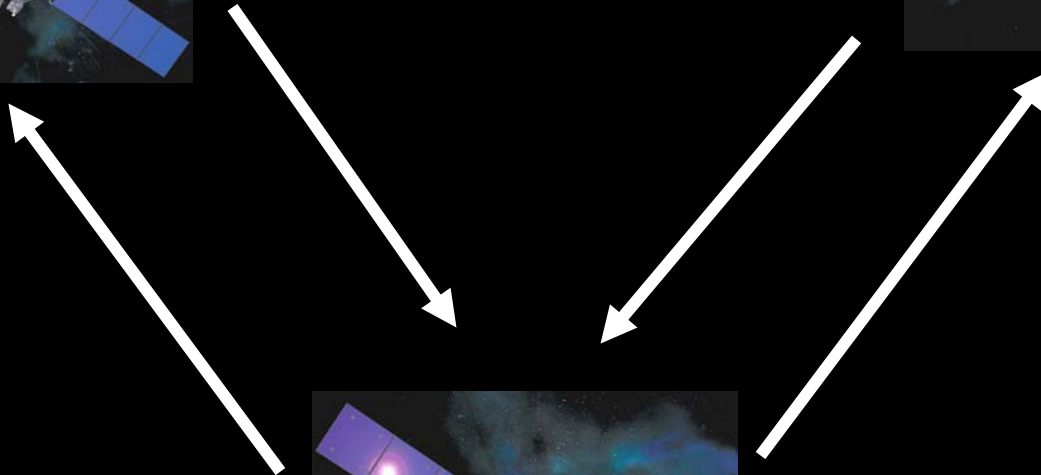
Transponders = 16
Leased = 12
Available Power 95%



Transponders = 12
Leased = 11
Available Power 80%



Transponders = 11
Leased = 11
Available Power 70%



Transponders = 16
New Leased = 12+1=13
Available Power 95%



Transponders = 12
New Leased = 11+1 = 12
Available Power 80%



transfer 1 program

Can only transfer
1 program

This preserves
overall revenue



Transponders = 9
Leased = 11
Available Power 65%

11-9 = 2 programs to transfer

Transponders = 16
Leased = 16 Fully booked
Available Power 95%



Transponders = 12
New Leased = 11+1=12
Available Power 80%



No room for 1
additional program

Can only transfer
1 program

This loses one
program of revenue
= \$1.5 million/yr



Transponders = 9
Leased = 11
Available Power 65%

11-9 = 2 programs to transfer

Transponders = 16
Leased = 12
Available Power 95%



Company B

Satellite has room
but it is either
1) Too far away or
2) Wrong company

Transponders = 12
New Leased = 11+1=12
Available Power 80%



Company A

No room for 1
additional program

Can only transfer
1 program

This loses one
program of revenue
= \$1.5 million/yr



Company A

Transponders = 9
Leased = 11
Available Power 65%

11-9 = 2 programs to transfer