LIGO OPEN SCIENCE CENTER (LOSC) S5 DATA TIME DEPENDENCE OF DUTY CYCLES AND SPACETIME DETECTION VOLUMES

Gary LaMotte and Jonah Kanner

gary.lamotte@ligo.org

Presented: LOSC Meeting 03/12/2014

DCC Document: LIGO-G1400427-v2

Goals

- Utilize LOSC data to evaluate Duty Cycles (DC) and All Sky Average Space-Time Volume (ST VOL) Detection Ranges for a typical expected Compact Binary Coalescence (CBC)
- Motivation:
  1) Desire to determine if time of day or day of the week enhances or hinders detection of a CBC
  2) Determine if horizon distance depends on time of day or just if an interferometer is “on”
  3) Assess for improvement in the ability of LIGO to make a detection over the course of a few months
- Evaluate DC and ST VOL detection ranges as function:
  1) Time of Day (Mainly day vs night)
  2) Workweek vs Weekend
  3) Improvement over the course of months
- Additional Goal: Assess difficulty/ease for an individual outside university affiliation/LIGO Scientific Collaboration (LSC) to access and analyze data on an ordinary laptop computer

Data Source

- LIGO OPEN SCIENCE CENTER (LOSC) DATA FROM SCIENCE RUN 5 (S5)
- Specifically from 2007, starting 04/30/2007 and continuing for 4 1/2 months, thru 09/09/2007
- Hanford H1 IFO(Hanford, Washington)
- Reason This Data Selected: Long-Term Consistently High Duty Cycle (Based on LOSC website DC Plots)

Approach

- PC Laptop
- Home Hi Speed Internet (10 to 15 Meg)
- Data File Downloaded--> Analyzed (Python 2.7 Code) --> Deleted (Laptop storage limitation)--> Repeat Next File
- Fastest Time: 12 Days Data in 12 Hours (overnight)
- Slowest: 4 nights needed for 12 days data
- Realistically: About 30 NIGHTS needed to download 4 1/2 months of LOSC data.---Absolute MINIMUM time: 11 nights
- Speed often slowed for last half of 12 hour download, Possible causes:
  1) ISP restriction
  2) RAM issue (not being cleared)

LOSC Website Download Issues

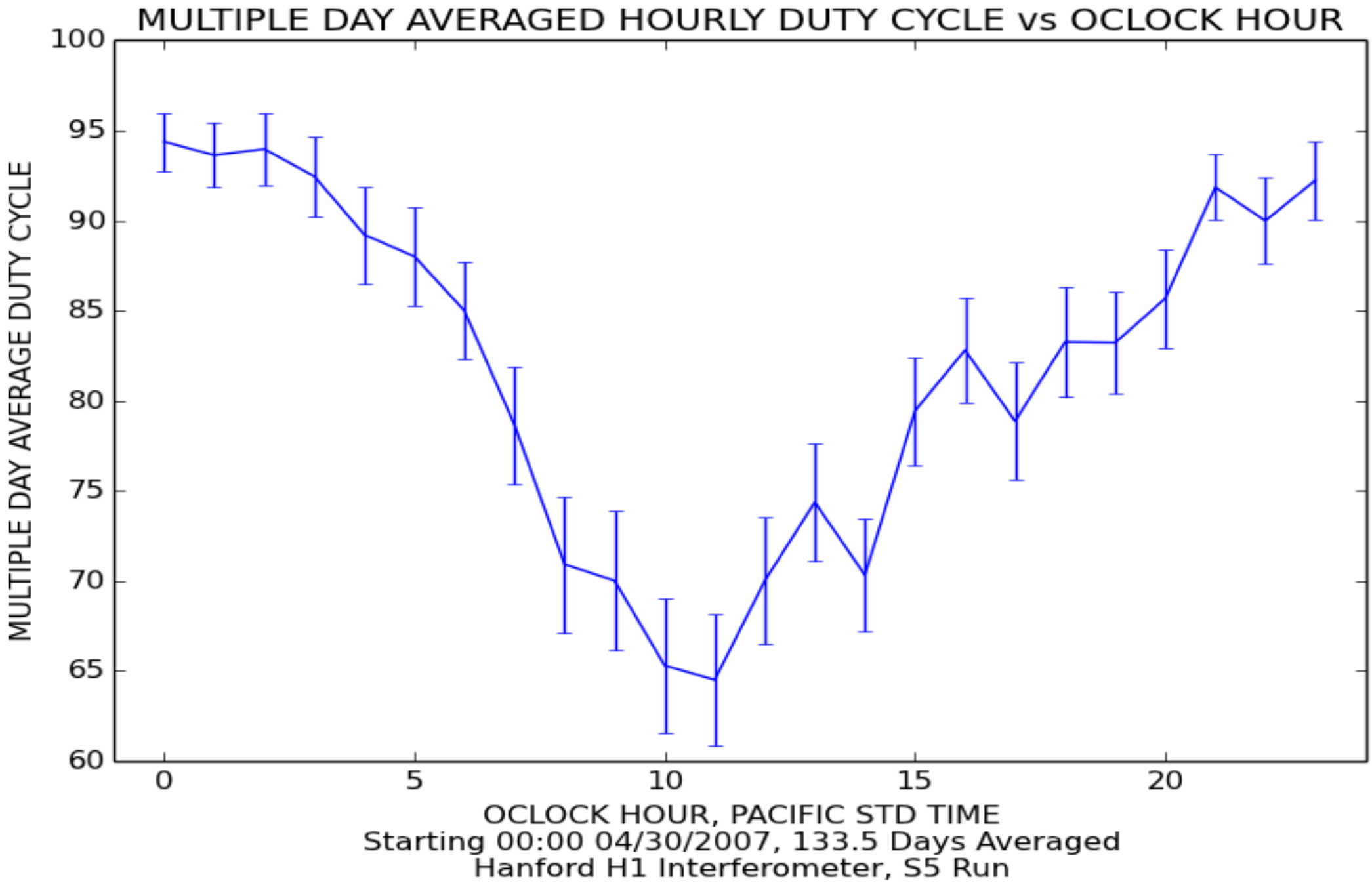
- Easy: Manually Download Individual Files (LOSC Tutorial)
- Harder: Downloading Groups of Files. LOSC Tutorial instructions for multiple file download didn't work for my PC
- The Fix:
  1) Upgrade from "LIGO Guest" to full access
  2) LOSC team help thru firewalls to access LOSC data
  3) Write unique Python CODE for Sequential File Download
- Conclusion: Sequential automated LOSC file downloads weren't simple to do for me as an outsider

Duty Cycle

- Definition: Percentage of time equipment is working properly in an hour, day, week, etc.
- Working properly: LIGO Interferometer (IFO) in "Science mode" (SCI)
- In Course of an Hour (approx. time length of a file):
  - The IFO may drift in and out of SCI mode once, a few times or not at all
  - Only "GOOD" or SCI mode data is analyzed. Remainder: Excess noise
  - May thus be multiple "Segments" of SCI mode data per file
  - Each Segment must be analyzed separately

Duty Cycle vs O'Clock Hour – Plot (below)

- What's Being Plotted:
  - 133 days of data with DC analyzed hourly
  - One Hour bins for total of 24 bins <===> o'clock hours
  - Average Hourly DC plotted
- How Calculated:
  - Each Downloaded FILE: Slightly longer than 1 Hour
  - RATIO: GOOD Data Segment TIME LENGTHS are Summed / TOTAL Elapsed TIME of File===> DUTY CYCLE for that File
  - Each File's DC is assigned to nearest o'clock hour
  - Average each O'clock Hour separately for 133 days of data, then plot
  - Error Bars: (Standard Deviation of Averaged DCs)/(Number Averaged)$^{1/2}$


MULTIPLE DAY AVERAGED HOURLY DUTY CYCLE vs OCLOCK HOUR
MULTIPLE DAY AVERAGE DUTY CYCLE
100
95
90
85
80
75
70
65
60
0
5
10
15
20
OCLOCK HOUR, PACIFIC STD TIME
Starting 00:00 04/30/2007, 133.5 Days Averaged
Hanford H1 Interferometer, S5 Run

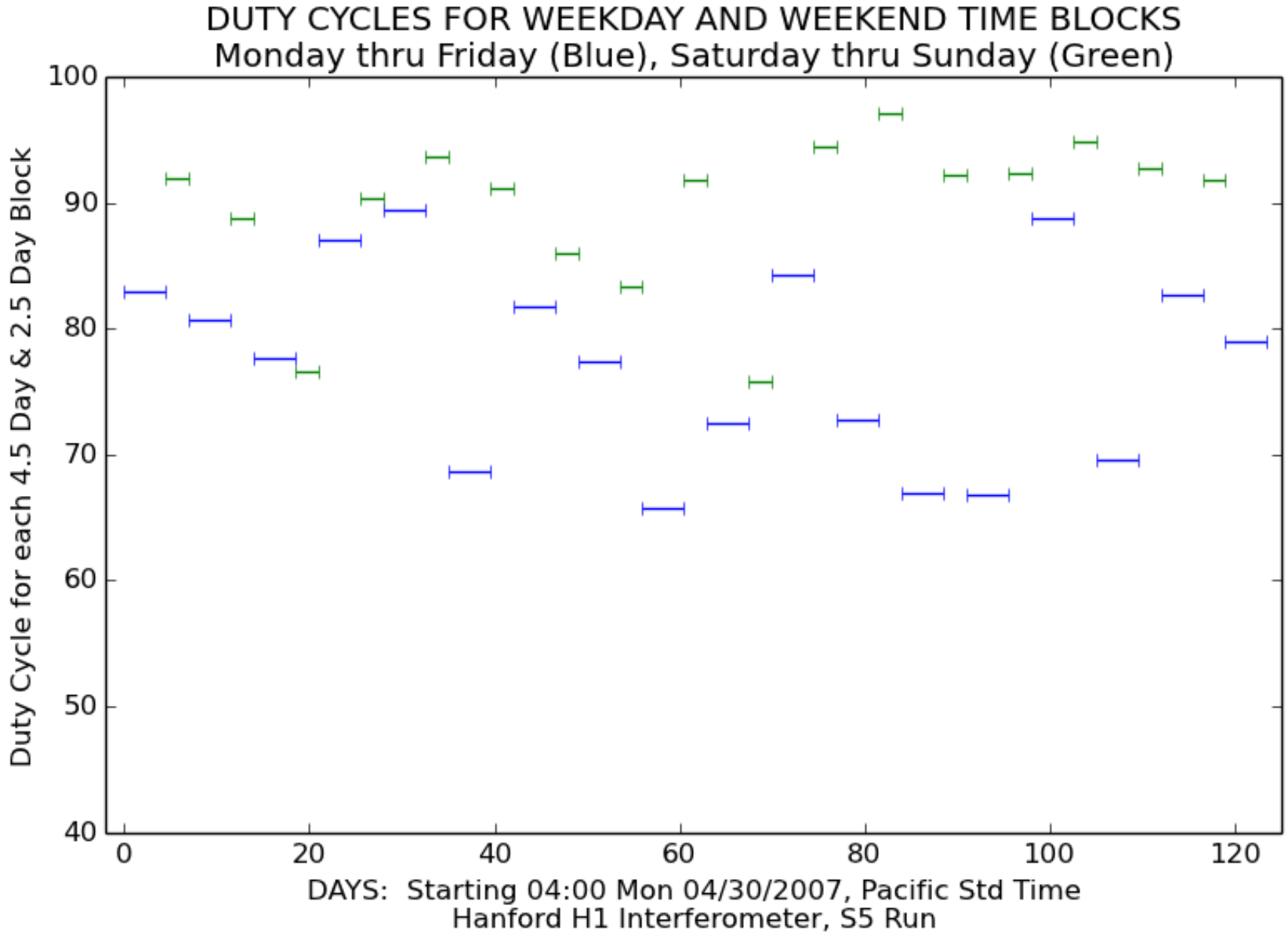
Results

- Plot is based on Pacific Std Time, the Time Zone of the Hanford, Washington LIGO IFO
- Clear DAY/NIGHT difference in DC--Highest: Midnight----Lowest: 11:00 a.m.
- DC Range is 64% to 94%
- AVG = 82%
- Interesting Features:
  - Smoothly Varying Curve with NO Abrupt Changes "SINE WAVE" Appearance
  - Night-Time DC is Very High!
  - Day-time DC down Max of 32% vs Night-time <===>A METRIC
  - Goal: Of course to further maximize Day-Time DC, Keep Night-time High

Duty Cycle vs Weekday-Weekend Time Blocks – Plot (below)

- What's Being Plotted:
  - ANALYZED DATA from 04/30/07 until 09/09/07
  - Each WEEK: Divided into 2 TIME BLOCKS: 5 DAY WORKWEEK & 2 DAY WEEKEND
  - LINE SEGMENTS IN PLOT:
    1) avg DC FOR 5 DAY WORKWEEK (BLUE)
    2) avg DC FOR 2 DAY WEEKEND (GREEN)
  - LENGTH of LINE SEGMENT <===>NUMBER of DAYS in SEGMENT
  - WEEKEND starts 4pm FRI---------WEEKDAYS start 4am MON
  - DUTY CYCLE PLOT SCALE: 40 ------>100%

- How Calculated:
  - Download MULTIPLE FILES to span the TIME BLOCKS: WORKWEEK or WEEKEND
  - Each FILE with ONE OR MORE Data SEGMENTS
  - RATIO: GOOD Data Segment TIME LENGTHS are Summed for TIME BLOCK / TOTAL Elapsed TIME in BLOCK ===> DUTY CYCLE for that BLOCK of TIME


DUTY CYCLES FOR WEEKDAY AND WEEKEND TIME BLOCKS
Monday thru Friday (Blue), Saturday thru Sunday (Green)
Duty Cycle for each 4.5 Day & 2.5 Day Block
100
90
80
70
60
50
40
0
20
40
60
80
100
120
DAYS: Starting 04:00 Mon 04/30/2007, Pacific Std Time
Hanford H1 Interferometer, S5 Run

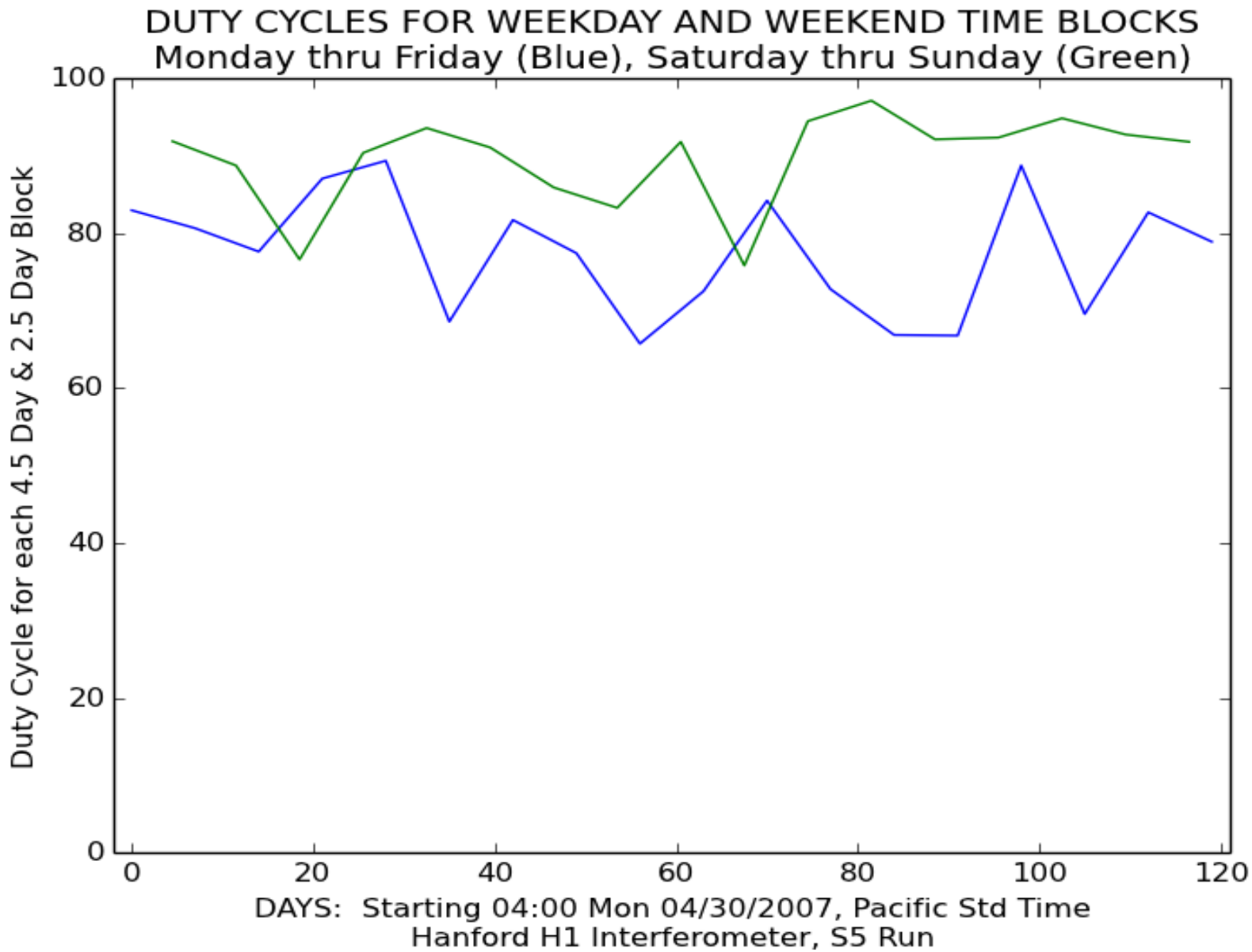
Results

- Plot is based on Pacific Std Time, the Time Zone of the Hanford Washington IFO
- Clear average WEEKEND/WEEKDAY DC DIFFERENCE
- WEEKEND AVG: 90 +/-6% MEDIAN: 92%
- WEEKDAY AVG: 78 +/-8% MEDIAN: 77%
- WEEKDAY AVG is 13% LESS than WEEKEND
- Interesting Features:
  - HIGHER DC when IFO is not being worked with as much ("LEFT ALONE")
  - DC difference is present but NOT large
  - 13% DIFFERENCE can be used as a METRIC

A More Intuitive Plot of Weekday-Weekend Duty Cycle

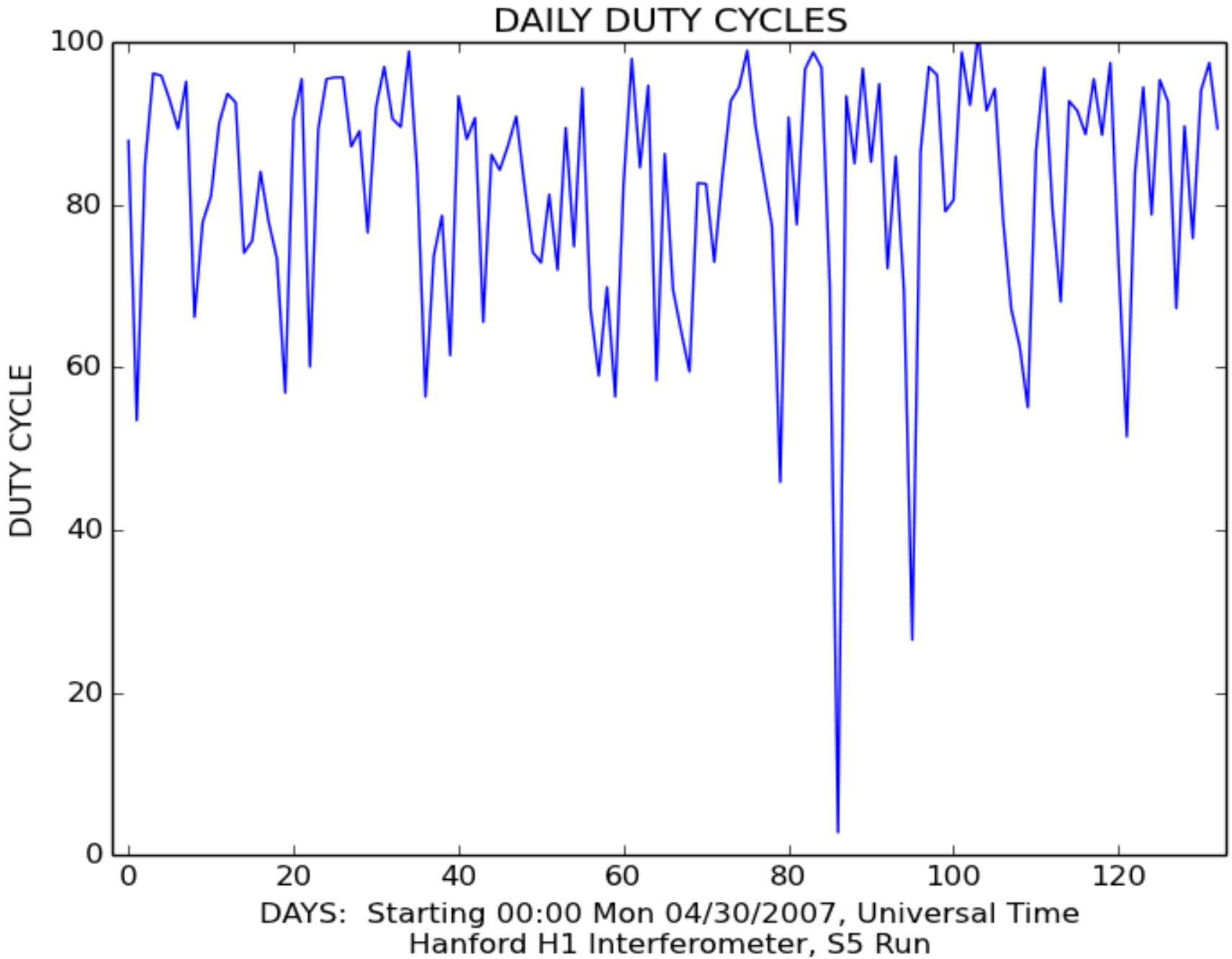
- What's Being Plotted:

  - **SAME** Weekday-Weekend DC RESULTS as ABOVE PLOT
  - DISCONTINUOUS WEEKEND line SEGMENTS are CONNECTED, same for WEEKDAYS
  - PLOT RESCALED: 0----->100%


DUTY CYCLES FOR WEEKDAY AND WEEKEND TIME BLOCKS
Monday thru Friday (Blue), Saturday thru Sunday (Green)
Duty Cycle for each 4.5 Day & 2.5 Day Block
100
80
60
40
20
0
0
20
40
60
80
100
120
DAYS: Starting 04:00 Mon 04/30/2007, Pacific Std Time
Hanford H1 Interferometer, S5 Run

Daily Duty Cycle Over 4 ½ Months – Plot (below)

- What's Being Plotted:
  - 133 days of data with DC analyzed Daily from 04/30/07 until 09/09/07
- How Calculated:
  - Analyze MULTIPLE FILES to span each DAY containing even more Data Segments
  - RATIO: SCI Data Segment Time Lengths are Summed for 24 Hours / Total Elapsed Time ===> DUTY CYCLE for that Day
  - DUTY CYCLE plotted vs DAY since 04/30/2007


DAILY DUTY CYCLES
DUTY CYCLE
100
80
60
40
20
0
0
20
40
60
80
100
120
DAYS: Starting 00:00 Mon 04/30/2007, Universal Time
Hanford H1 Interferometer, S5 Run

Results

- Plot is based on Universal Time (Greenwich Mean Time) -----Used because of calculation ease
- Typical Range: 50 to 95%
- AVG = 82 +/-15%----------Median = 86%
- Interesting Features:
  - HOPED to see IMPROVEMENT in DC over several months with progressive MAINTAINENCE
  - NO such IMPROVEMENT seen
  - Actually see transient SIGNIFICANT DECLINE in DC for 3 days btwn 77 and 96 DAYS OUT

ALL-SKY AVERAGE DETECTED SPACE-TIME VOLUMES

Basics of a complex calculation applied to each “good” downloaded data segment

Motivation: Desire to determine actual VOLUME OF SKY a CBC may be observable in.

- Most likely first observed CBC: Neutron Star / Neutron Star (NS/NS) Coalescence---Near Solar Mass

  1) Time length of inspiral: Several seconds
  2) Frequency of inspiral: Most sensitive LIGO range
  3) Population Density of NSs: Fairly high
  4) Choose 1.4 Solar Mass NS/1.4 Solar Mass NS Coalescence

Ingredients for Calculation:

1) Field Equations of General Relativity (GR)====> GR Deviations from Newtonian Gravity Binary elliptical orbit --> producing INSPIRAL

    Equations Used: 2nd Order Post-Newtonian Approximation to Field Equations

2) Also from GR, a predicted maximum orbital frequency reached at end of inspiral called FISCO (frequency of innermost stable circular orbit)

    Serves as an UPPER LIMIT of a key integration step

3) Concept of a "Matched Filter" Template--> Mathematically predicted timeseries waveform expected during CBC.

        If this template matches a signal received a detection is confirmed

Additional Ingredients:

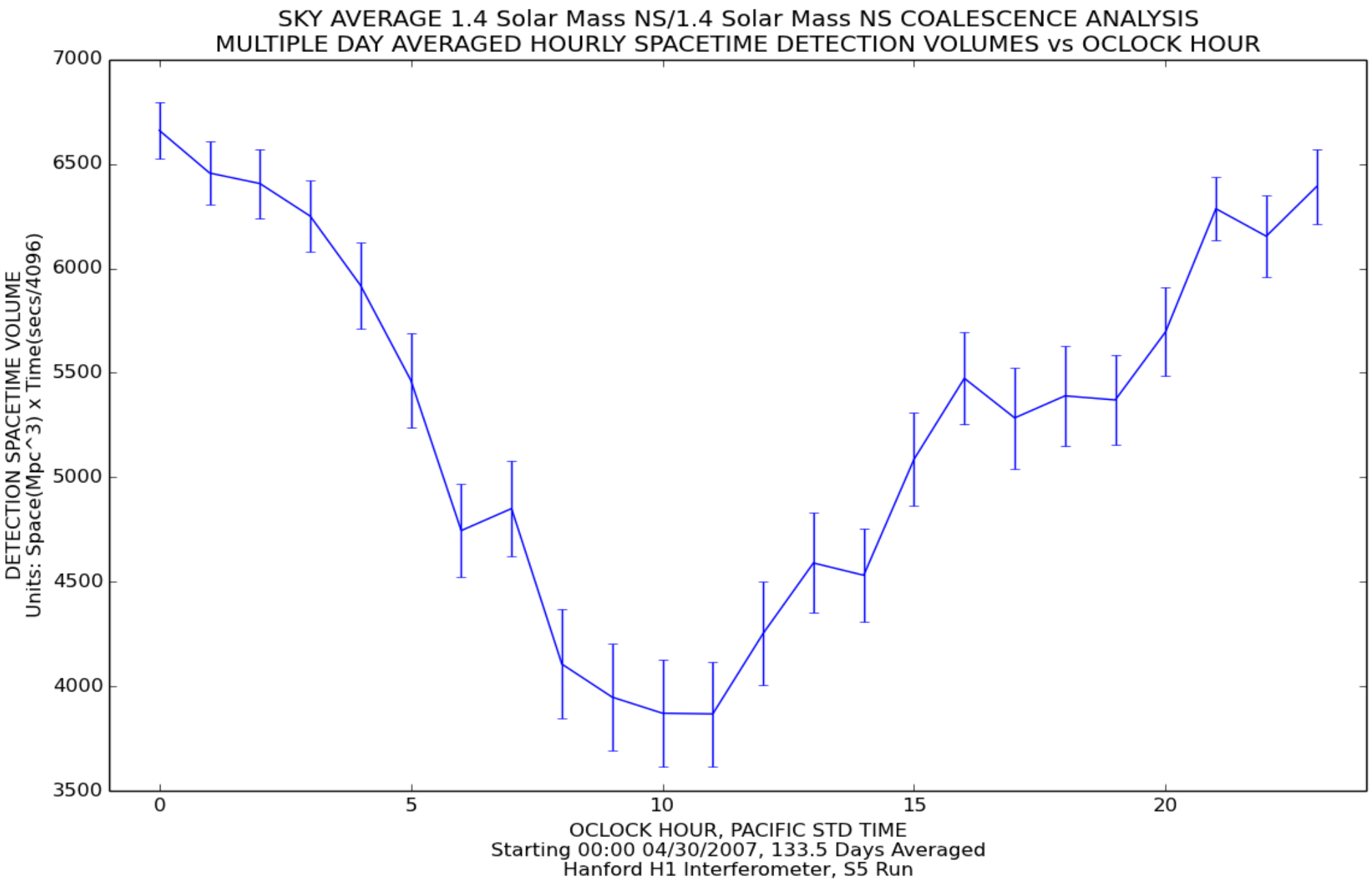
4) Large amount of data stream NOISE===> Calculate Power Spectral Density of noise and template with noise
5) Put ingredients together and obtain a height of signal greater than noise as a function of CBC distance away from earth.
6) Require Signal-to-Noise Ratio (SNR) > 8 to confirm a detection
7) Code written to calculate MAXIMUM DISTANCE for a detection under ideal conditions and a general ALL-SKY DISTANCE (less ideal) ===> SKY VOLUME

    Basically both DISTANCES are function of Detector Noise and Masses of Binaries in the CBC

8) References at end

All-Sky Space-Time Detection Volumes (ST VOL) vs O'Clock Hour – Plot (below)

- What's Being Plotted:
  - 133 days of data with ST VOL analyzed hourly
  - One Hour bins for total of 24 bins <===> o'clock hours
  - Average Hourly ST VOL plotted
- How Calculated:
  - Each Downloaded FILE: Slightly longer than 1 Hour
  - Each Data Segment in File===> Max Detection distance (CONVERT TO VOLUME)
  - For Segments in file: VOLUME weighted by segment time length===> Overall Space-Time Detection Volume for File
  - Each File's ST VOL is assigned to nearest o'clock hour
  - Average each O'clock Hour separately for 133 days of data, then plot
  - Error Bars: (Standard Deviation of Average ST VOLs) / (Number Averaged)$^{1/2}$


SKY AVERAGE 1.4 Solar Mass NS/1.4 Solar Mass NS COALESCENCE ANALYSIS
MULTIPLE DAY AVERAGED HOURLY SPACETIME DETECTION VOLUMES vs OCLOCK HOUR
DETECTION SPACETIME VOLUME
Units: Space(Mpc^3) x Time(secs/4096)
7000
6500
6000
5500
5000
4500
4000
3500
0
5
10
15
20
OCLOCK HOUR, PACIFIC STD TIME
Starting 00:00 04/30/2007, 133.5 Days Averaged
Hanford H1 Interferometer, S5 Run

Results

- Plot is based on Pacific Std Time, the Time Zone of the Hanford Washington IFO
- Clear DAY/NIGHT difference in ST VOL; Highest: Midnight, Lowest: 11:00 a.m. (Same times as with Duty Cycle)
- ST VOLUME Range: (3,800 Mpc^3 to 6,700 Mpc^3) * (1 Time Unit)

  1 Time Unit Here is File Time Length = 4096s
- AVG = 5,294 +/-887 Mpc^3 * 1 Time Unit
- AVG NIGHT-TIME ST VOL: 5983 Mpc^3 * 1 Time Unit ----------(00:00 to 06:00 and 18:00 to 24:00)
- AVG DAYTIME ST VOL: 4605 Mpc^3 * 1 Time Unit ------(06:00 to 18:00)

IT IS THUS 30% MORE LIKELY TO MAKE A DETECTION DURING THE NIGHT THAN DURING THE DAY.

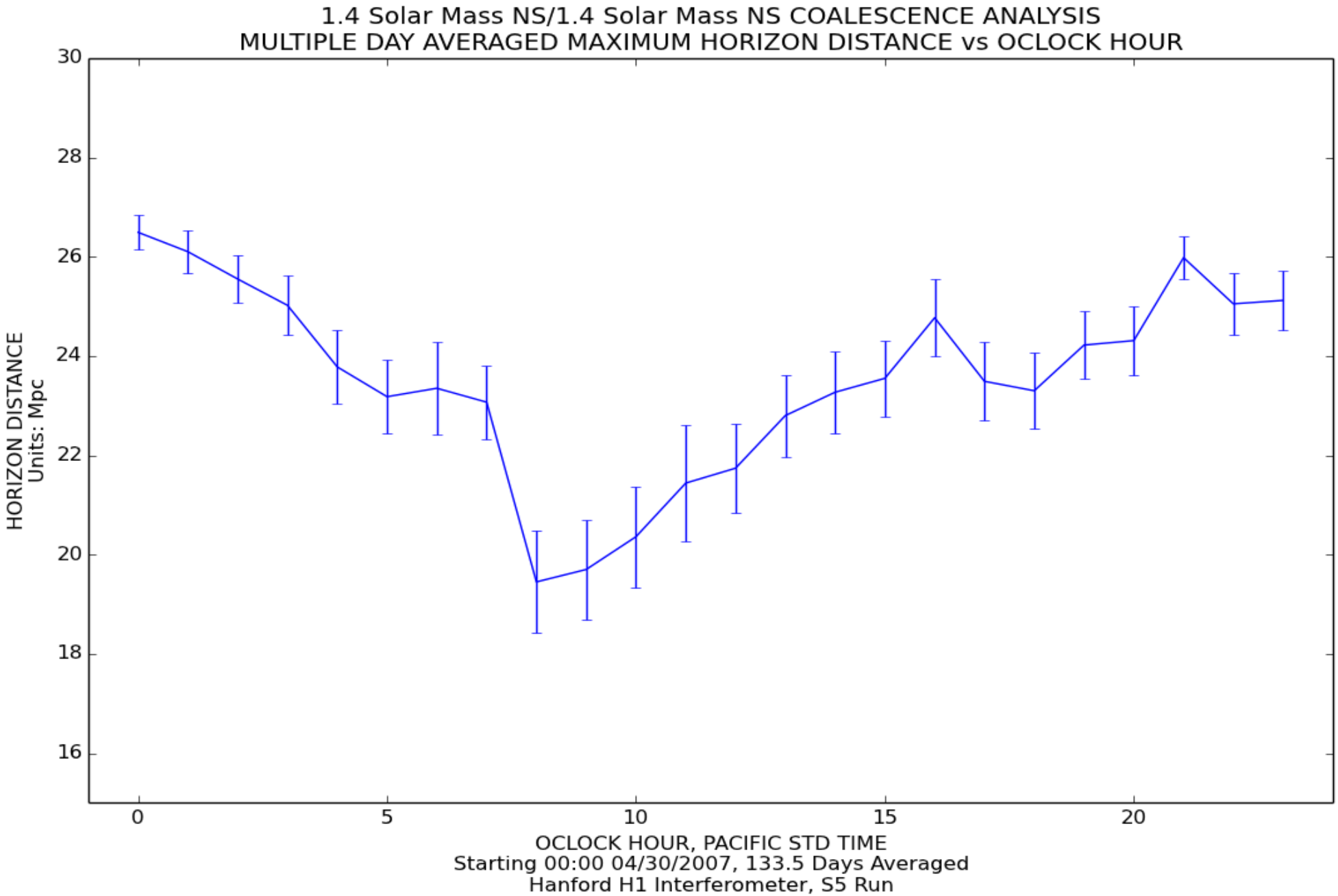
Interesting Features

- Smoothly Varying Curve with NO Abrupt Changes--"SINE WAVE" Appearance
- Day-time ST VOL down Max of 43% vs Night-time <===>A METRIC----------
  (vs DC down 32% below max)
- Goal: Of course to further maximize Day-Time ST VOLs (Night-Time is probably maxed out as IFO running at max design sensitivity for 2007 capability)

Note: Short Lived Transient Higher SPATIAL VOLUMES may make a more distant detection possible if very lucky even with typical AVERAGE ST VOL

Hourly Average Maximum Horizon Distance (HD) vs O'Clock Hour – Plot (below)

- What's Being Plotted:
  - 133.5 days of data with HD analyzed hourly
  - One Hour bins for total of 24 bins <===> o'clock hours
  - Average Hourly SEGMENT MAXIMUM HD plotted
- How Calculated:
  - Each Downloaded FILE: Slightly longer than 1 Hour
  - Each Data Segment in File===> Max Detection distance
  - For each Data Segment in an individual FILE, retain only the largest one of the Max Detection distances
  - Each File's SINGLE Max Detection DISTANCE is assigned to nearest o'clock hour
  - Average each O'clock Hour separately for 133.5 days of data, then plot
  - Error Bars: As before


1.4 Solar Mass NS/1.4 Solar Mass NS COALESCENCE ANALYSIS
MULTIPLE DAY AVERAGED MAXIMUM HORIZON DISTANCE vs OCLOCK HOUR
HORIZON DISTANCE
Units: Mpc
30
28
26
24
22
20
18
16
0
5
10
15
20
OCLOCK HOUR, PACIFIC STD TIME
Starting 00:00 04/30/2007, 133.5 Days Averaged
Hanford H1 Interferometer, S5 Run

Results

- EXCLUDES DC FROM THE ANALYSIS
- AVG NIGHT-TIME MAX HORIZON DISTANCE: 24.8 Mpc
- AVG DAYTIME MAX HORIZON DISTANCE: 22.2 Mpc
- FIRST IMPRESSION THEN: LIGO "SEES" 12% FARTHER AT NIGHT THAN DURING THE DAY
- NOT SO

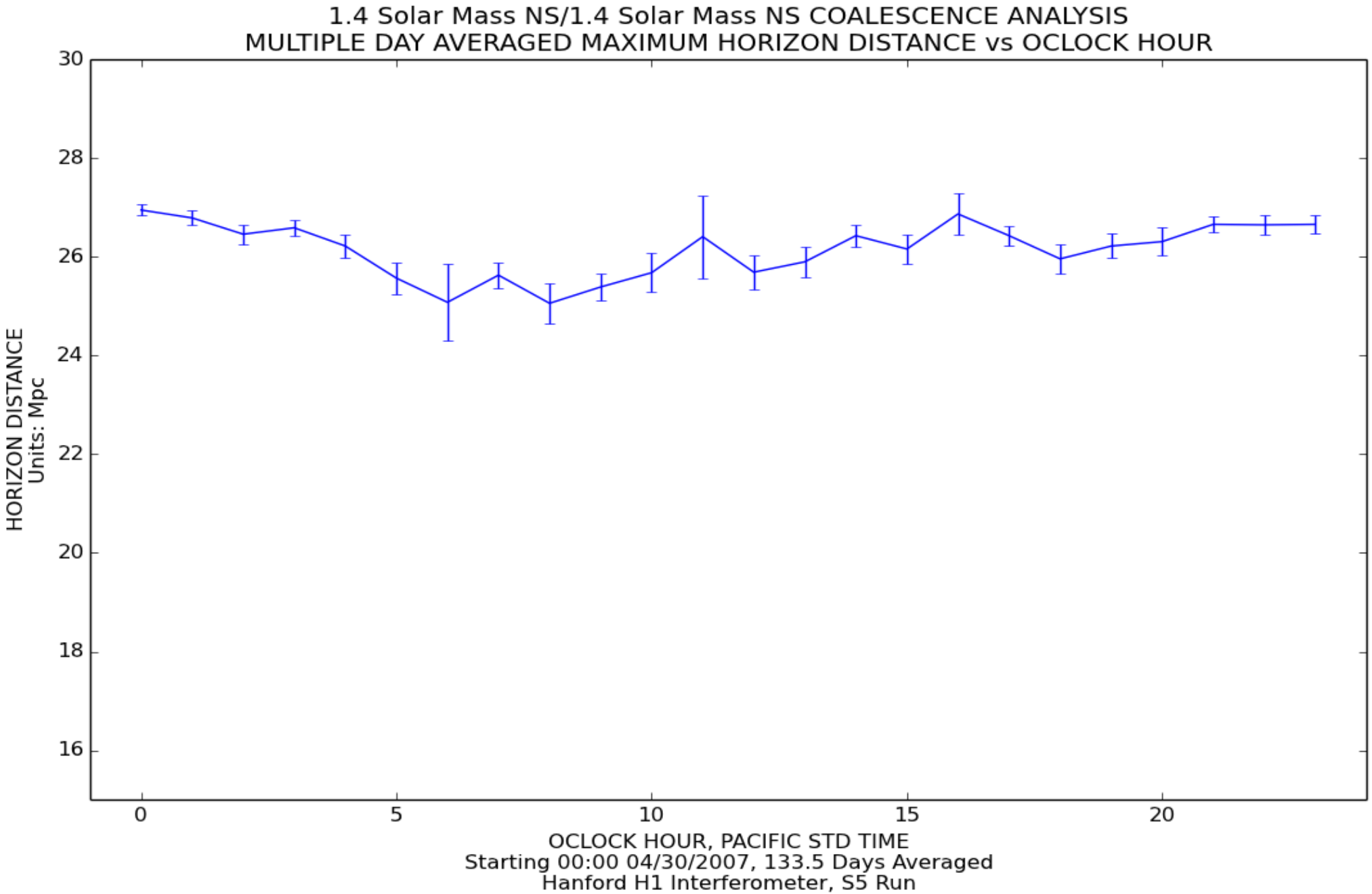
Modified Hourly Average Maximum Horizon Distance (HD) vs O'Clock Hour – Plot (below)

Modification:

FILES WITH A ZERO DISTANCE MAXIMUM ARE ELIMINATED FROM ANALYSIS THIS TIME

- What's Being Plotted:
  - 133.5 days of data with HD analyzed hourly
  - One Hour bins for total of 24 bins <===> o'clock hours
  - Average Hourly MAXIMUM HD plotted

- How Calculated:
  - Each Downloaded FILE: Slightly longer than 1 Hour
  - Each Data Segment in File===> Max Detection distance
  - For each Data Segment in an individual FILE, retain only the largest one of the Max Detection distances
  - Each File's SINGLE Max Detection DISTANCE is assigned to nearest o'clock hour
  - IF THE FILE'S SINGLE MAX DETECTION DISTANCE IS ZERO (NO DATA OBTAINED) IT IS ELIMINATED FROM THE ANALYSIS
  - Average each O'clock Hour separately for 133.5 days of data, then plot
  - Error Bars: As before


1.4 Solar Mass NS/1.4 Solar Mass NS COALESCENCE ANALYSIS
MULTIPLE DAY AVERAGED MAXIMUM HORIZON DISTANCE vs OCLOCK HOUR
HORIZON DISTANCE
Units: Mpc
30
28
26
24
22
20
18
16
0
5
10
15
20
OCLOCK HOUR, PACIFIC STD TIME
Starting 00:00 04/30/2007, 133.5 Days Averaged
Hanford H1 Interferometer, S5 Run

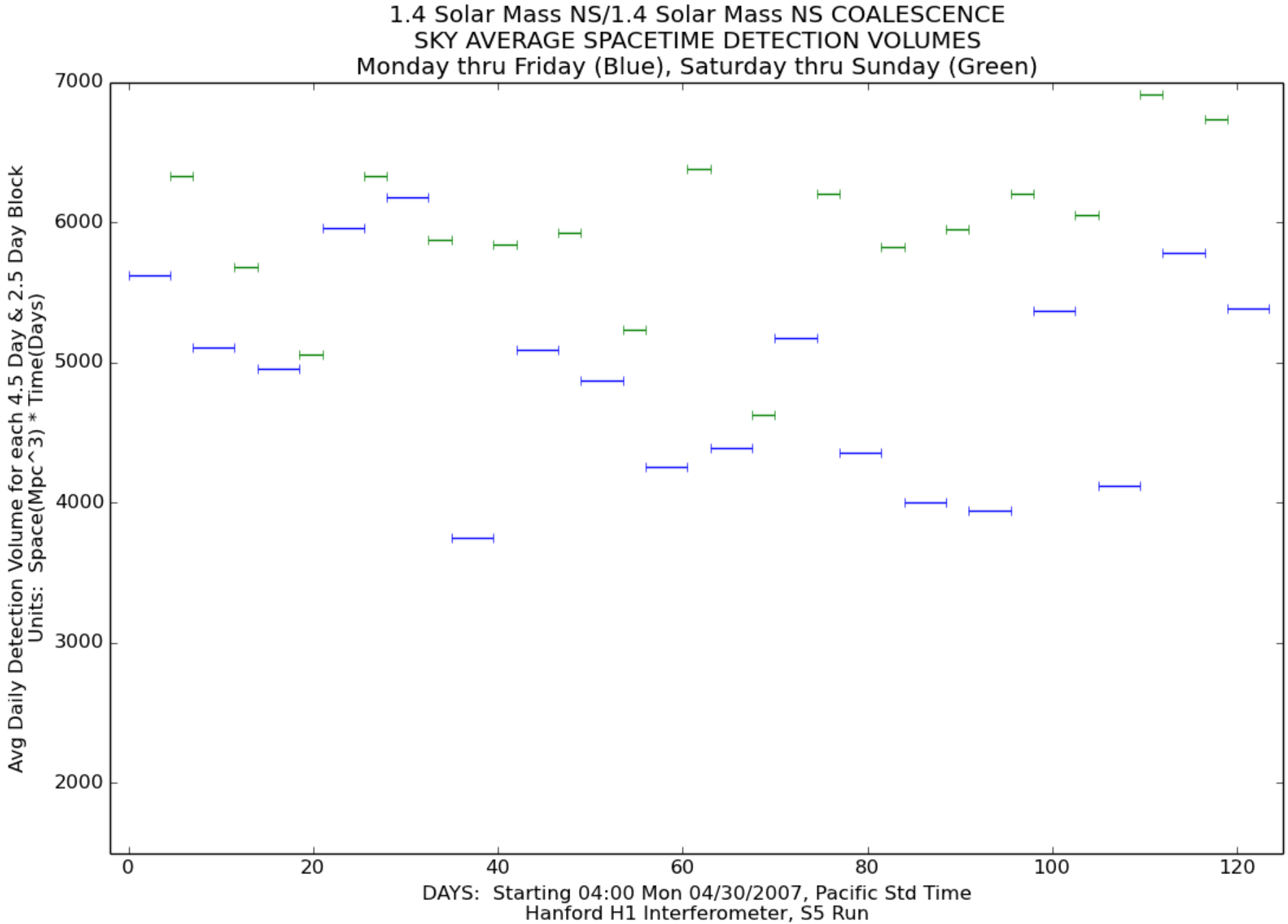
Results

- EXCLUDES ANY ZERO DISTANCE FILES
- AVG NIGHT-TIME MAX HORIZON DISTANCE: 26.3 Mpc
- AVG DAYTIME MAX HORIZON DISTANCE: 26.0 Mpc
- LIGO DOESN'T "SEE" ANY FURTHER AT NIGHT THAN DURING THE DAY (ONLY A NIGHT-TIME "IMPROVEMENT" OF 1.2%)
- THIS IS TRUE ONLY IF THE IFO IS ACTUALLY IN SCI MODE AT SOME TIME DURING A PARTICULAR HOUR AND ACQUIRES AT LEAST SOME DATA
- DC IS LESS DURING THE DAY THAN AT NIGHT (DESCRIBED EARLIER)

All-Sky Space-Time Detection Volumes (ST VOL) vs Weekday-Weekend Time Blocks – Plot (below)

- What's Being Plotted:
  - ANALYZED DATA from 04/30/07 until 09/09/07
  - Each WEEK: Divided into 2 TIME BLOCKS: 5 DAY WORKWEEK & 2 DAY WEEKEND
  - LINE SEGMENTS IN PLOT:
    1) avg ST VOL FOR 5 DAY WORKWEEK TIME BLOCK (BLUE)
    2) avg ST VOL FOR 2 DAY WEEKEND TIME BLOCK (GREEN)
  - LENGTH of LINE SEGMENT <===>NUMBER of DAYS in SEGMENT
  - WEEKEND starts 4pm FRI---------WEEKDAYS start 4am MON
  - Y-Axis in Units of Mpc^3 x Day

- How Calculated:
  - Download MULTIPLE FILES to span the TIME BLOCKS: WORKWEEK or WEEKEND
  - Evaluate all contained DATA SEGMENTS individually
  - Each Data Segment in File===> Max Detection distance (CONVERT TO VOLUME)
  - For Segments: VOLUME weighted by segment time length===> Overall Space-Time Detection Volume in a TIME BLOCK
  - PLOT ST VOL avgs for lengths of time blocks===> LINE SEGMENTS


1.4 Solar Mass NS/1.4 Solar Mass NS COALESCENCE
SKY AVERAGE SPACETIME DETECTION VOLUMES
Monday thru Friday (Blue), Saturday thru Sunday (Green)
Avg Daily Detection Volume for each 4.5 Day & 2.5 Day Block
Units: Space(Mpc^3) * Time(Days)
7000
6000
5000
4000
3000
2000
0
20
40
60
80
100
120
DAYS: Starting 04:00 Mon 04/30/2007, Pacific Std Time
Hanford H1 Interferometer, S5 Run

Results

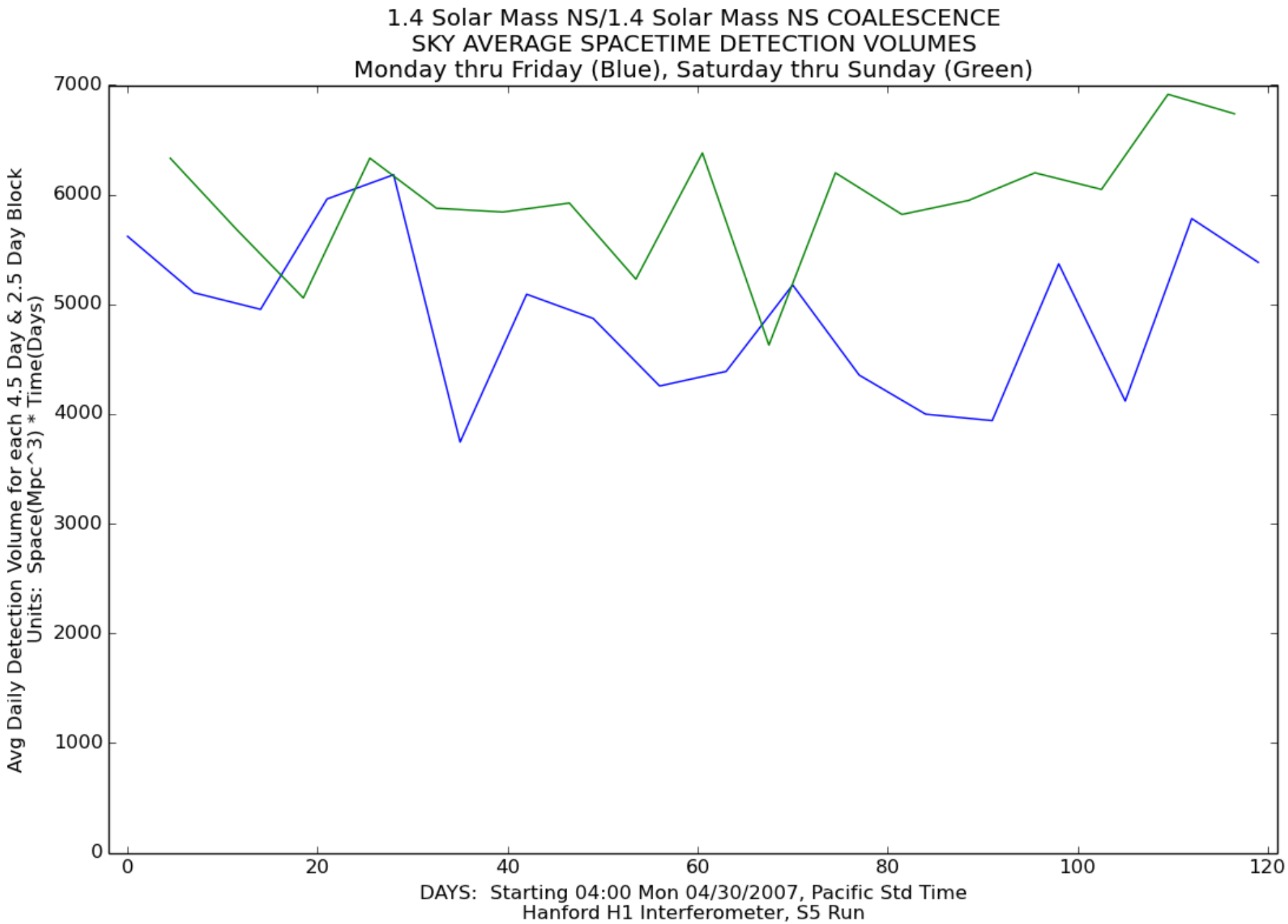
- Plot is based on Pacific Std Time, the Time Zone of the Hanford Washington IFO
- Clear average WEEKEND/WEEKDAY ST VOL DIFFERENCE
- WEEKEND AVG: 5,950 +/-560 Mpc^3 * Day------MEDIAN: 5,947
- WEEKDAY AVG: 4,905 +/-720 Mpc^3 * Day------MEDIAN: 5,023
- WEEKDAY AVG is 18% LESS than WEEKEND----------(Vs 13% LESS for DC)

Interesting Features:

- HIGHER ST VOL when IFO is not being worked with as much ("LEFT ALONE")
- ST VOL difference is present but NOT large
- 18% DIFFERENCE can be used as a METRIC
- SIMILAR VALUES of DECREASE (18% ST VOL and 13% DC suggest that DC is the primary cause for decrease in ST VOL, other factors less important

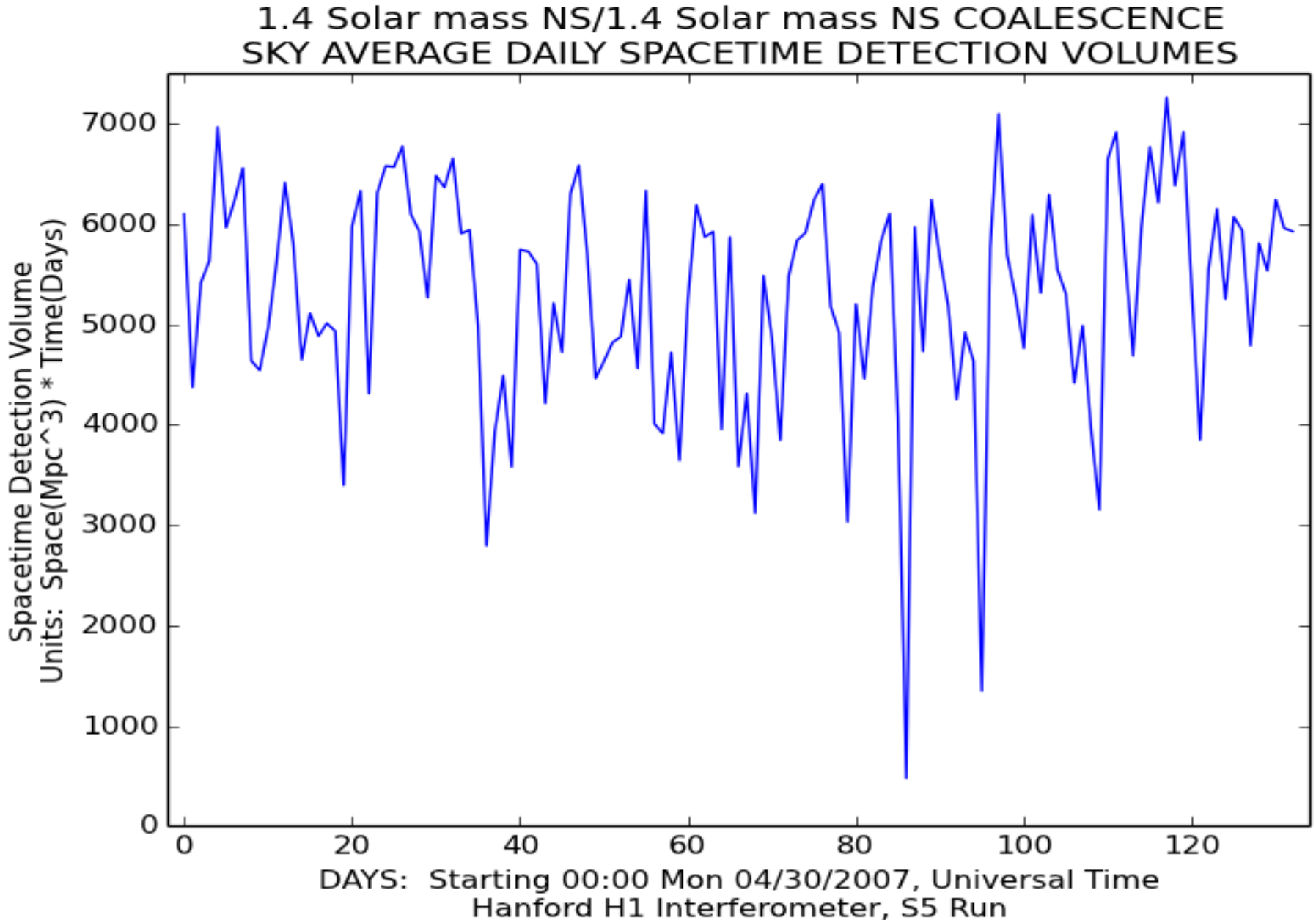
A More Intuitive Plot of Weekday-Weekend Space-Time Volume:

- What's Being Plotted:
  - **SAME** Weekday/Weekend ST VOL RESULTS as ABOVE PLOT
  - DISCONTINUOUS WEEKEND line SEGMENTS are CONNECTED, same for WEEKDAYS
  - PLOT RESCALED from 0


1.4 Solar Mass NS/1.4 Solar Mass NS COALESCENCE
SKY AVERAGE SPACETIME DETECTION VOLUMES
Monday thru Friday (Blue), Saturday thru Sunday (Green)
Avg Daily Detection Volume for each 4.5 Day & 2.5 Day Block
Units: Space(Mpc^3) * Time(Days)
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
DAYS: Starting 04:00 Mon 04/30/2007, Pacific Std Time
Hanford H1 Interferometer, S5 Run

Daily All-Sky Space-Time Detection Volumes (ST VOL) Over 4 ½ Months – Plot (below)

- What's Being Plotted:
  - 133 days of data with ST VOL analyzed Daily from 04/30/07 until 09/09/07
- How Calculated:
  - Analyze MULTIPLE FILES to span each DAY containing even more Data Segments
  - Evaluate all contained DATA SEGMENTS individually
  - Each Data Segment in File===> Max Detection distance (CONVERT TO VOLUME)
  - For Segments: VOLUME weighted by segment time length===> Overall Space-Time Detection Volume in an INDIVIDUAL DAY
  - ST VOL plotted vs DAY since 04/30/2007


1.4 Solar mass NS/1.4 Solar mass NS COALESCENCE
SKY AVERAGE DAILY SPACETIME DETECTION VOLUMES
Spacetime Detection Volume
Units: Space(Mpc^3) * Time(Days)
0
1000
2000
3000
4000
5000
6000
7000
0
20
40
60
80
100
120
DAYS: Starting 00:00 Mon 04/30/2007, Universal Time
Hanford H1 Interferometer, S5 Run

Results

- Plot is based on Universal Time (Greenwich Mean Time) -----Used because of calculation ease
- Typical Range: 3,000 to 7,000 Mpc^3 x Day
- AVG = 5,300 +/-1,095 Mpc^3 x Day
- Median = 5,483

Interesting Features:

- HOPED to see IMPROVEMENT in ST VOL over several months with progressive MAINTAINENCE
- NO such IMPROVEMENT seen
- July 2007 trends slightly lower for the whole month vs before and after
- Actually see transient SIGNIFICANT DECLINE for 2 days in ST VOL btwn 84 and 96 DAYS OUT

Conclusions:

DURING THE TIMES THE H1 IFO IS EVALUATED, FROM 04/30/07 THRU 09/09/07:

- DUTY CYCLES AND ALL-SKY SPACE-TIME DETECTION VOLUMES DEPEND ON HUMAN ACTIVITY WORK SCHEDULE CYCLES SUCH AS:
  1) DAY VS NIGHT AND
  2) WEEKDAYS VS WEEKEND

- THE IFO RUNS QUITE WELL THE VAST MAJORITY OF THE TIME WHEN "LEFT ALONE"

- DECREASE IN SPACE-TIME DETECTION VOLUMES CORRELATES VERY CLOSELY WITH DECREASES IN DUTY CYCLES
  - IN BOTH TIME OF OCCURENCE AND MAGNITUDE AND IN ALL LIKELIHOOD IS THE PRIMARY ETIOLOGY

Additional Conclusions:

- NO IMPROVEMENT TREND OCCURS WITH DUTY CYCLES AND ALL-SKY SPACE-TIME DETECTION VOLUMES OVER THE MONTHS EVALUATED DESPITE MAINTAINENCE
  - AND PRESUMABLY ATTEMPTS TO INCREASE SENSITIVITY

- 2 WEEKS OF LOSC DATA CAN BE DOWNLOADED ONTO AN ORDINARY PC THRU ORDINARY HOME DOWNLOAD SPEEDS IN ABOUT 12 HOURS WHEN ALL IS OPTIMAL

- GREAT EASE OF BEING ABLE TO MANUALLY DOWNLOAD LOSC DATA, ONE FILE AT A TIME

- SIGNIFICANT DIFFICULTIES WITH SEQUENTIAL AUTOMATED LOSC DATA FILE DOWNLOADS FOR THIS PC USER OUTSIDE THE LSC AND UNIVERSITY AFFILIATION

WHEN IS LIGO MOST LIKELY TO MAKE A FIRST DETECTION??

30% MORE LIKELY TO MAKE A GRAVITATIONAL WAVE DETECTION AT NIGHT THAN DURING THE DAY!

REFERENCES:

1) Bruce Allen, et al. FINDCHIRP: An algorithm for detection of gravitational waves from inspiraling compact binaries. arXiv:gr-qc/0509116
2) J. Abadie, et al. Class. Quantum Grav., 27:173001, 2010
3) The LIGO Scientific Collaboration: J. Abadie, et al. Sensitivity to gravitational waves from compact binary coalescenses achieved during LIGO's fifth and Virgo's first science run, 2010. arXiv:1003.2481