A Study of the Compact Water Vapor Radiometer for the Karl G. Jansky Very Large Array

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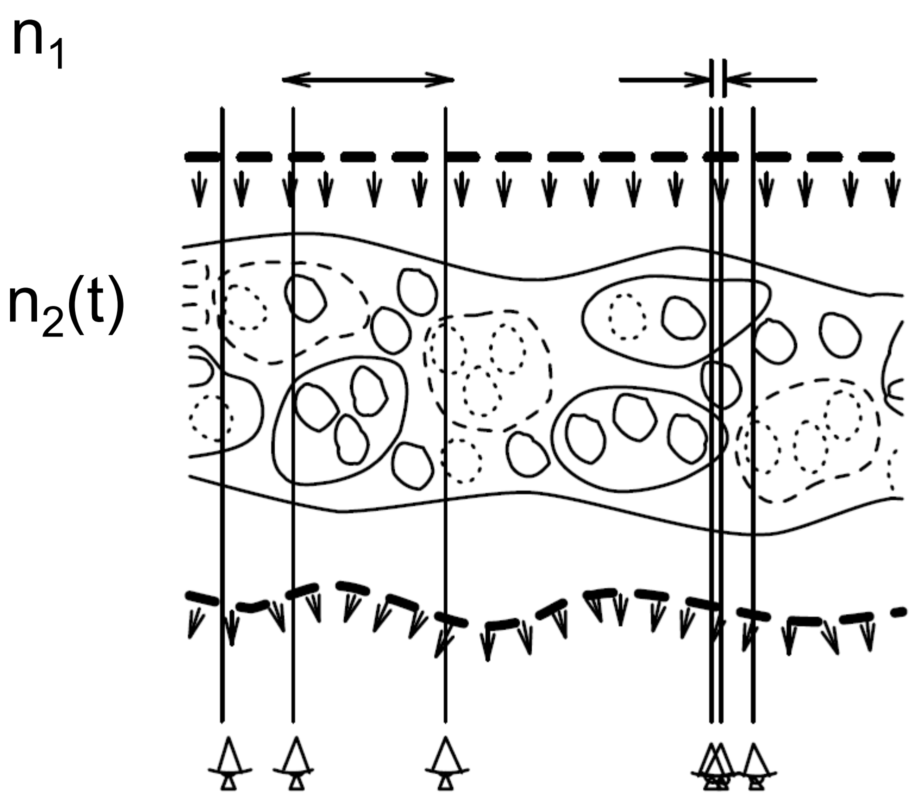
Acknowledgment: NRAO Graduate Summer Research Assistantship Program



v_c ~ 10 m/s →

$$\mathcal{L} \simeq \mathcal{L}_D + \mathcal{L}_V \simeq 0.228 P_0 + 6.3 w$$

Carilli & Holdaway (1999), Desai (1993), Thompson, Moran, & Swenson (2001)

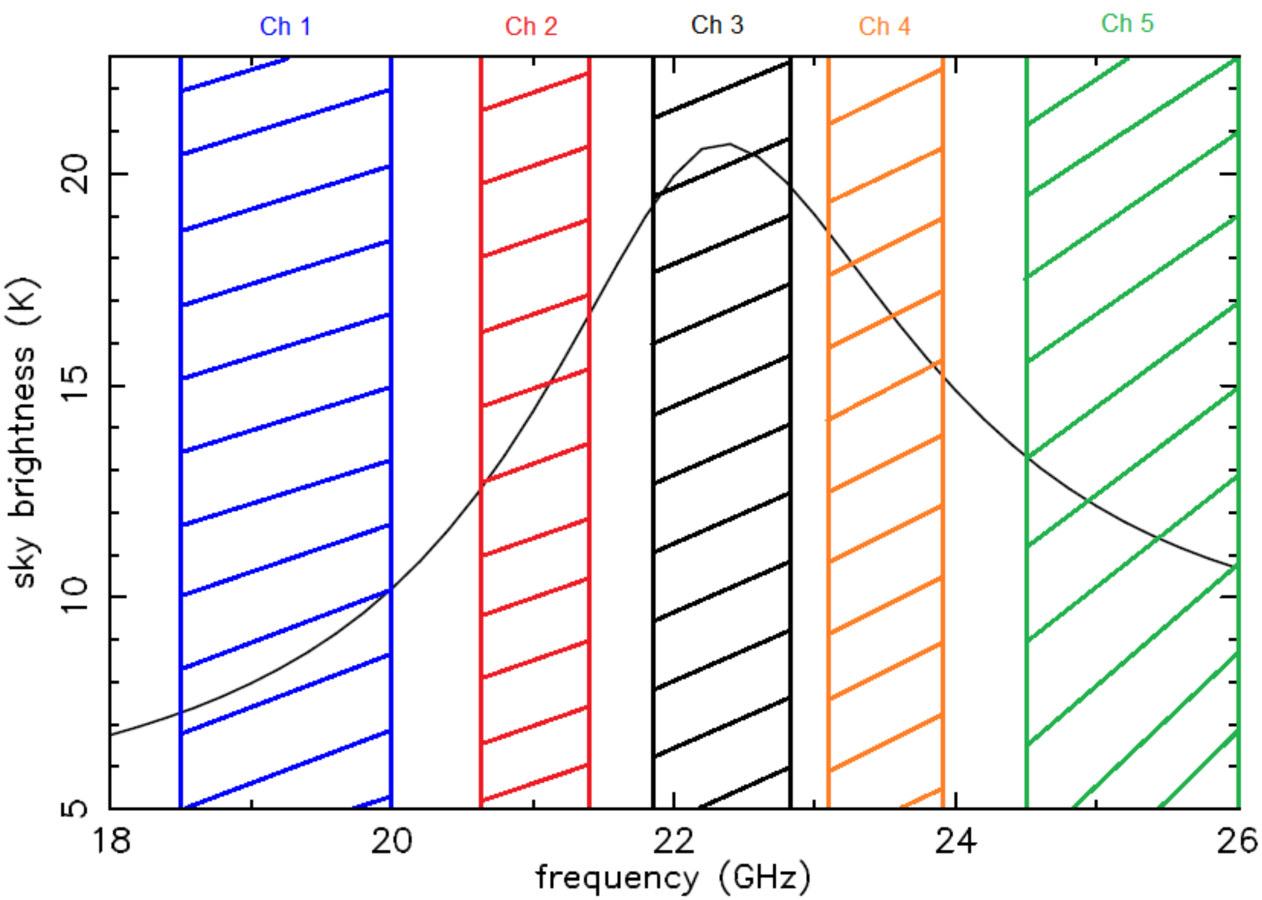
Water Vapor Radiometry

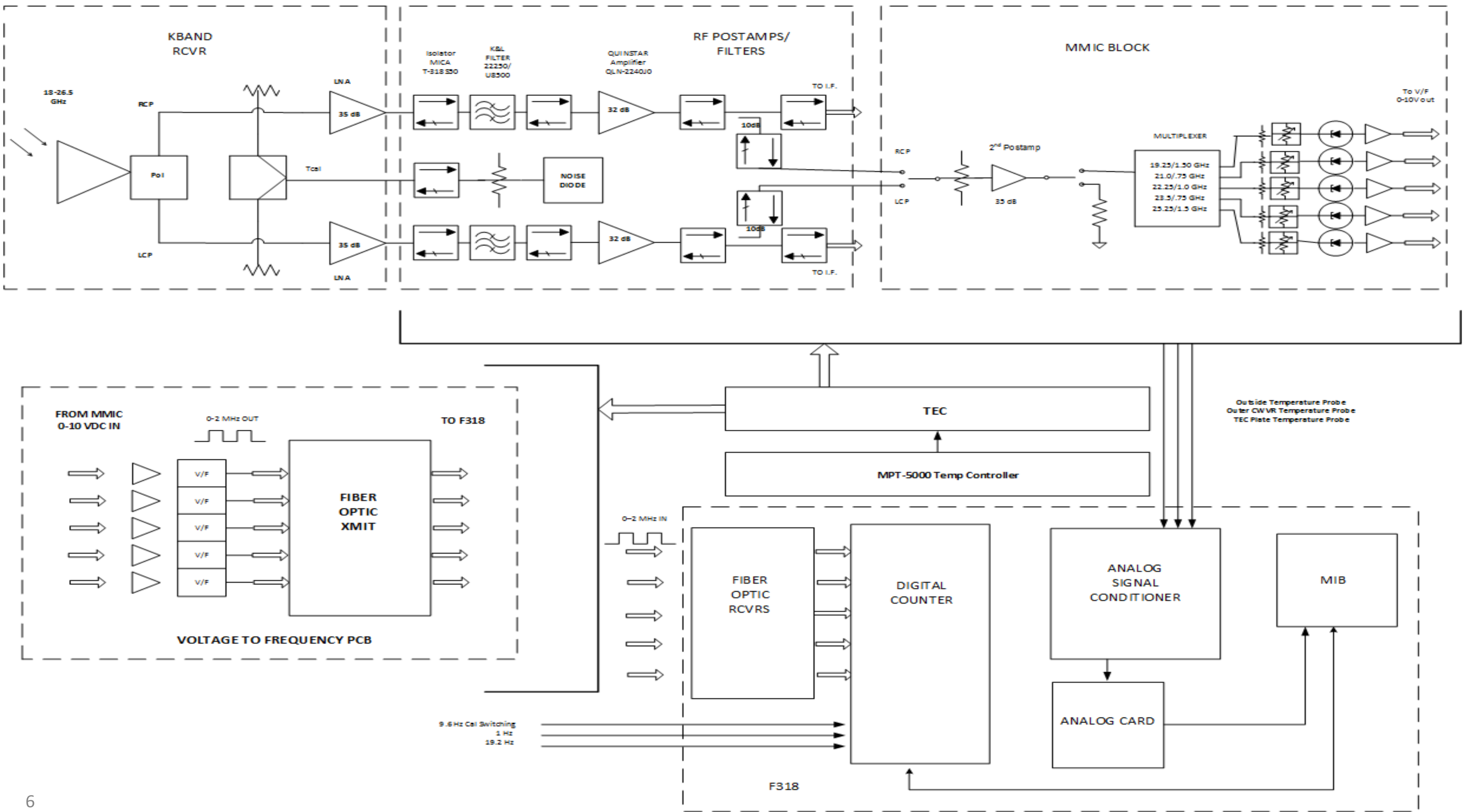
- WV ⟶ Continuum & Line Emission, T_{sky}
- ΔWV ⟶ $\Delta T_{sky} \propto \Delta\varphi_{astro}$ ⟶ Empirical Correction Factor
- Liquid water ⟶ Continuum
- Observe 22 GHz WV line
- Channels at line & away from line
- Distinguish liquid water & WV

Objectives

- Characterize CWVR prototype in lab
- Gain stability
- Temperature stability
- Channel isolation
- Dynamic range
- Pathfinder to evaluate WVR for EVLA and ngVLA

CWVR 5 Channels

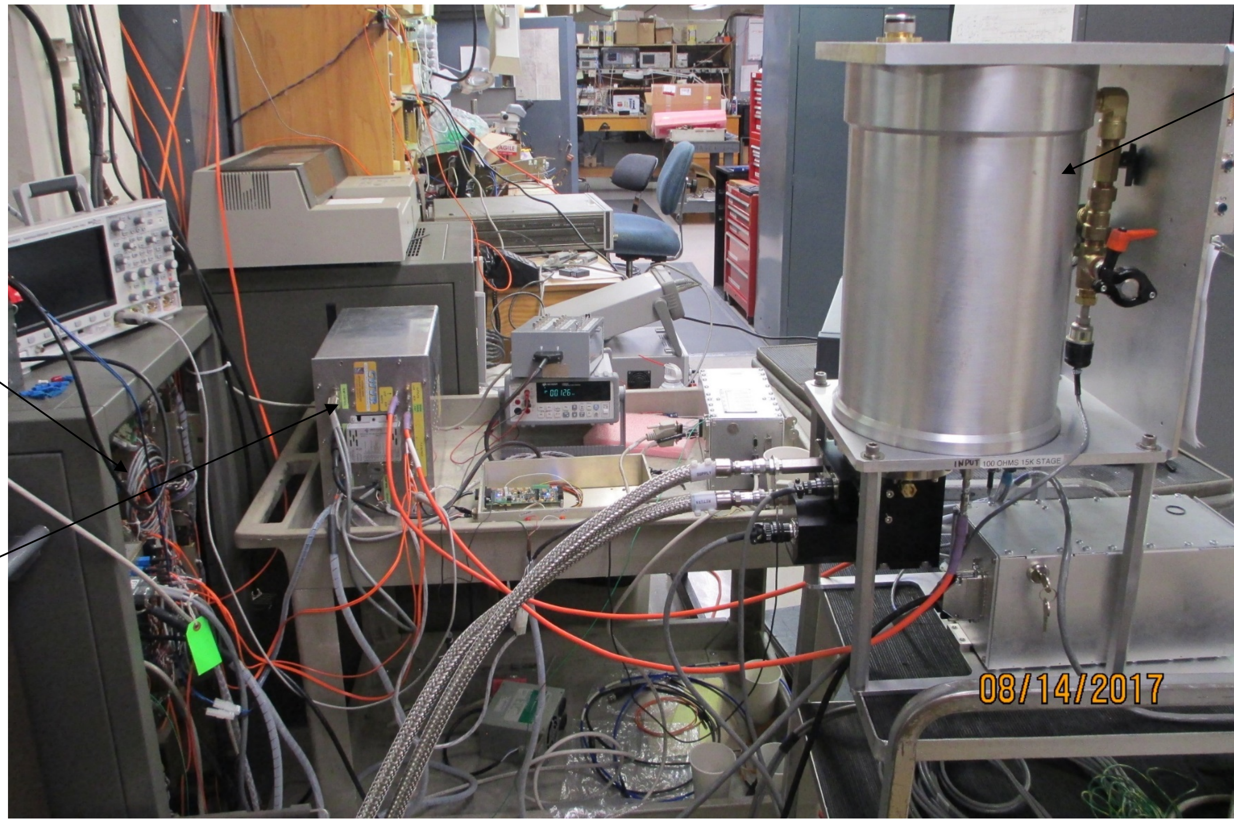



KBAND
RCVR
18-26.5
GHz
RCP
LCP
Pol
Tcal
LNA
35 dB
Isolator
MICA
K&L
FILTER
QUINSTAR
Amplifier
32 dB
RF POSTAMPS/
FILTERS
NOISE
DIODE
TO I.F.
10dB
MMIC BLOCK
2nd Postamp
35 dB
MULTIPLEXER
19.25/1.50 GHz
21.0/.75 GHz
22.25/1.0 GHz
23.5/.75 GHz
25.25/1.5 GHz
To V/F
0-10V out
TEC
MPT-5000 Temp Controller
Outside Temperature Probe
Outer CWVR Temperature Probe
TEC Plate Temperature Probe
FROM MMIC
0-10 VDC IN
0-2 MHz OUT
TO F318
V/F
FIBER
OPTIC
XMIT
VOLTAGE TO FREQUENCY PCB
0-2 MHz IN
FIBER
OPTIC
RCVRS
DIGITAL
COUNTER
ANALOG
SIGNAL
CONDITIONER
MIB
ANALOG CARD
9.6Hz Cal Switching
1 Hz
19.2 Hz
F318

Instrument Setup

Dewar

F318



CWVR

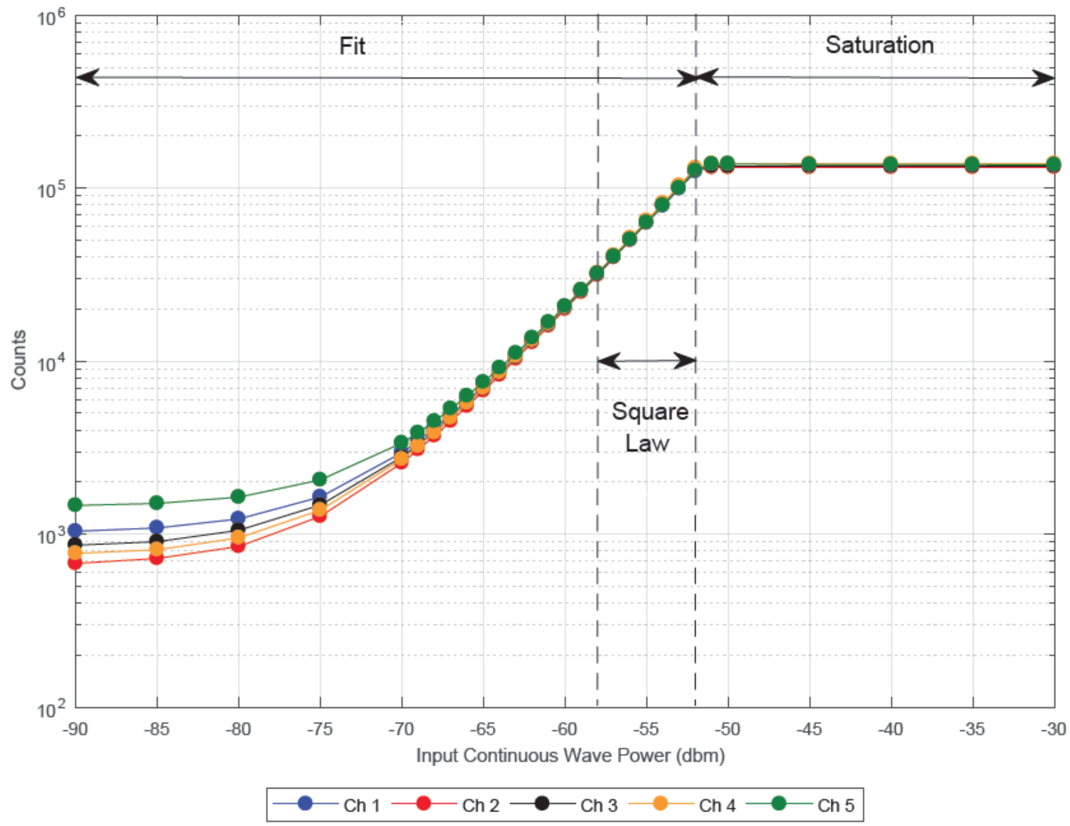
- Gain Stability Requirements (4 Channels)
  - $\Delta T \propto \Delta P_{in} = w_2P_2 + w_3P_3 + w_4P_4 + w_5P_5$
  - $w_2 = -0.5$, $w_3 = 1$, $w_4 = -0.5$, $w_5 = 0.25$
  - ~ 35 μm of WV ⟶ 220 μm of electrical path delay (λ/30 for λ = 7 mm)
  - For ΔT_{rms} ~ 25 mK, $T_{i,rms}$ ~ 20 mK
  - For T_{sys} = 50 – 100 K and τ = 2.5 - 10^3 seconds
  - **$\Delta g / g \sim 2.5 – 5 \times 10^{-4}$** **$\Delta g_i / g_i \sim 2 – 4 \times 10^{-4}$**

Observable — Individual Channel

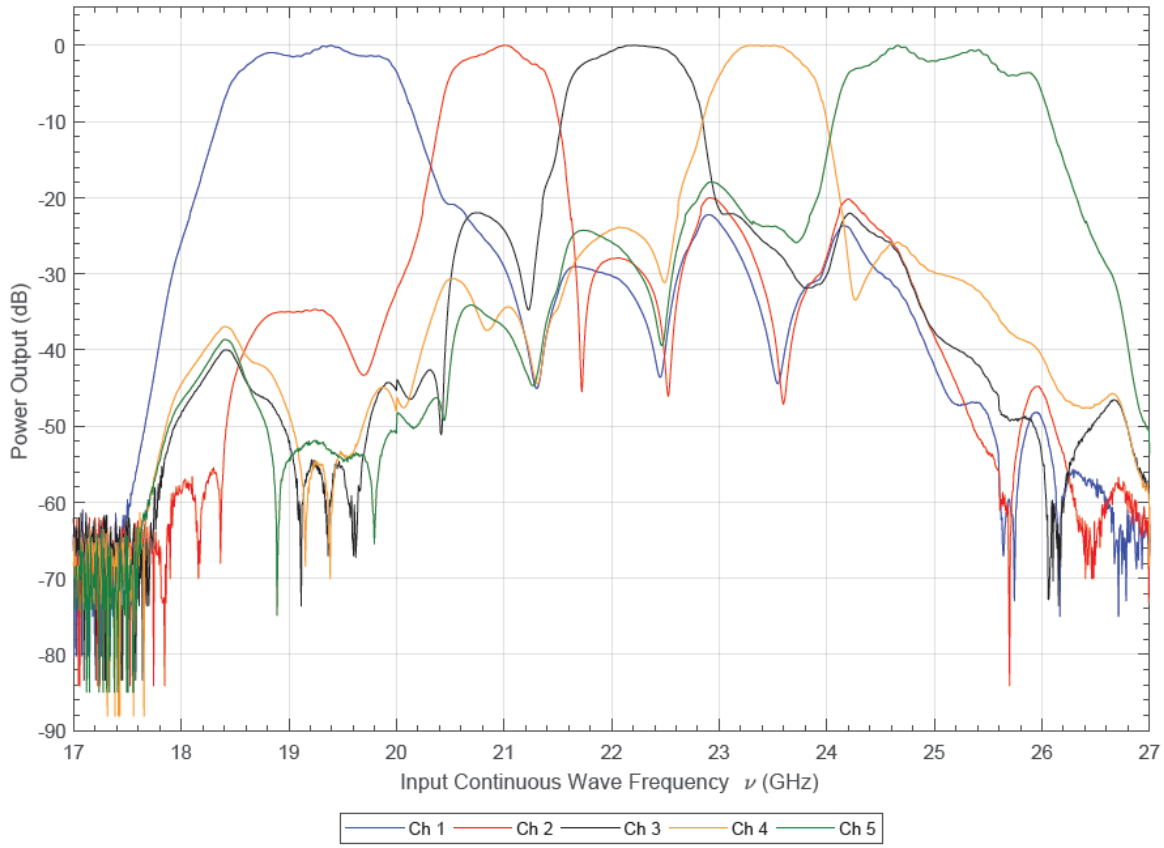
- Channel Isolation Requirements (4 Channels)
  - **~ - 20 dB**
  - ~ 1% power leakage between any two channels

Chandler et al (2005), Butler (1999)

Dynamic Range



Channel Isolation

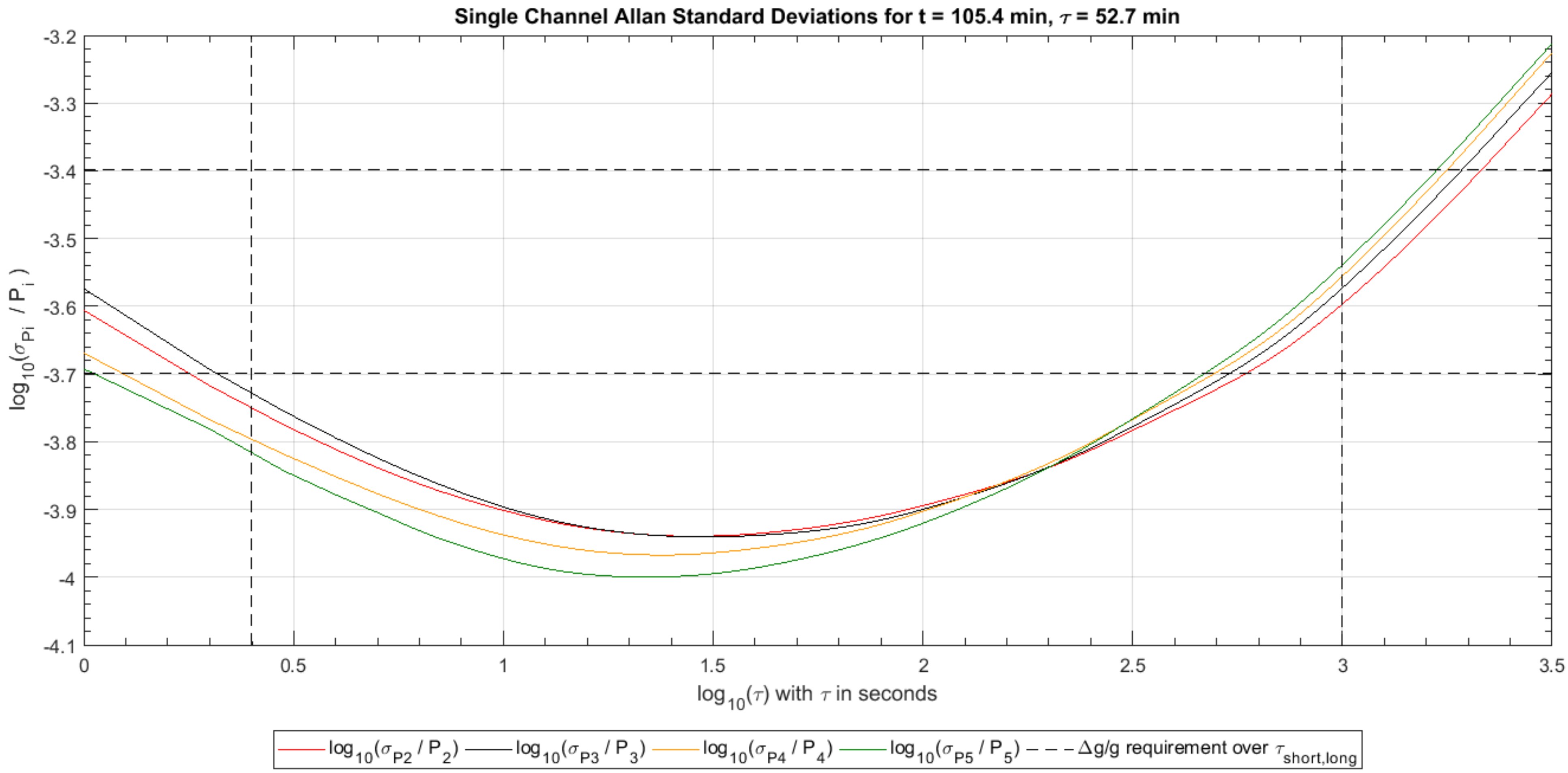


Channel Isolation Values

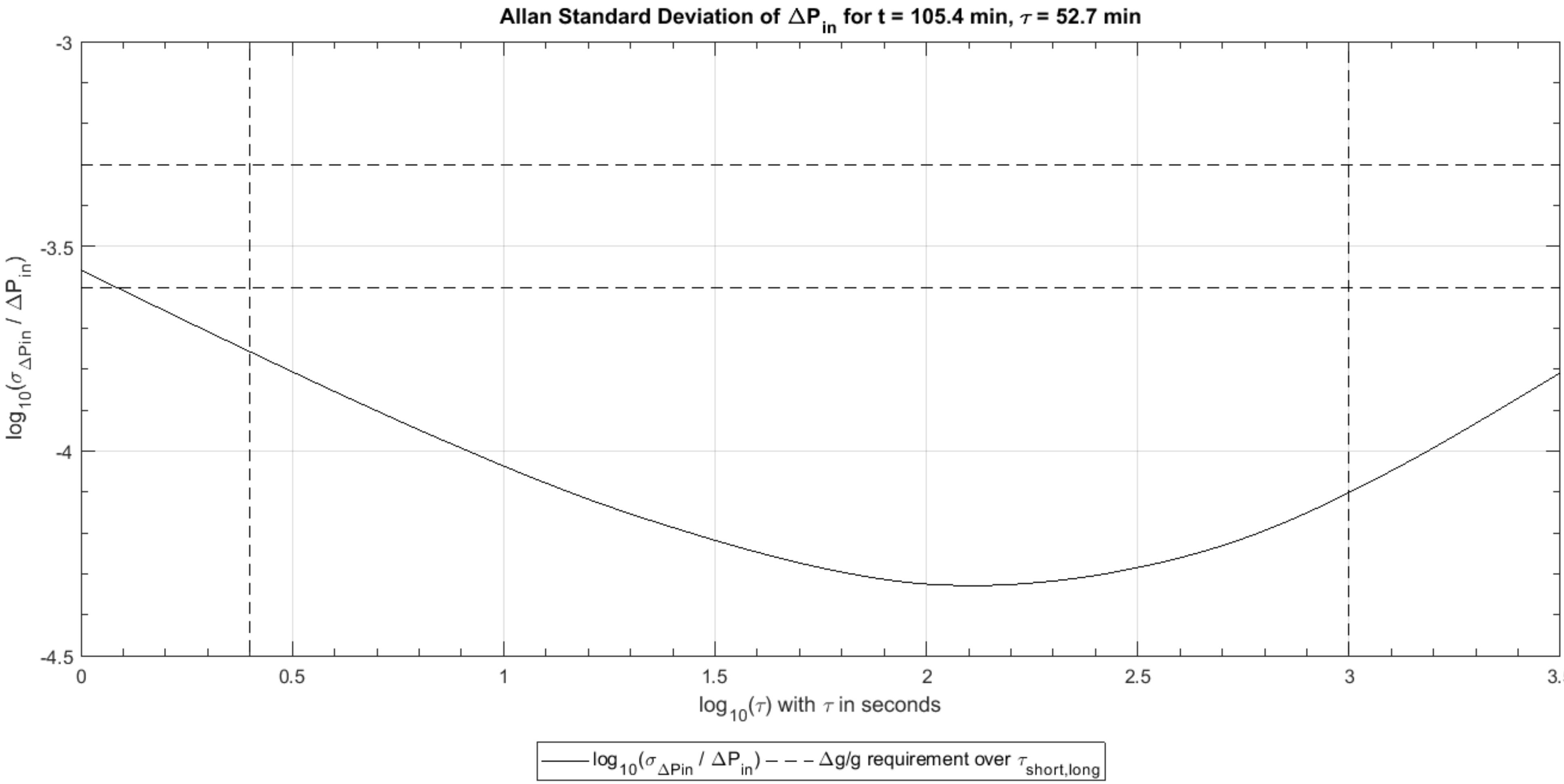
- $$IS_{xy} = \frac{\int_{\nu_i}^{\nu_f} P_x(\nu) P_y(\nu) d\nu}{\int_{\nu_i}^{\nu_f} P_y(\nu) d\nu}$$

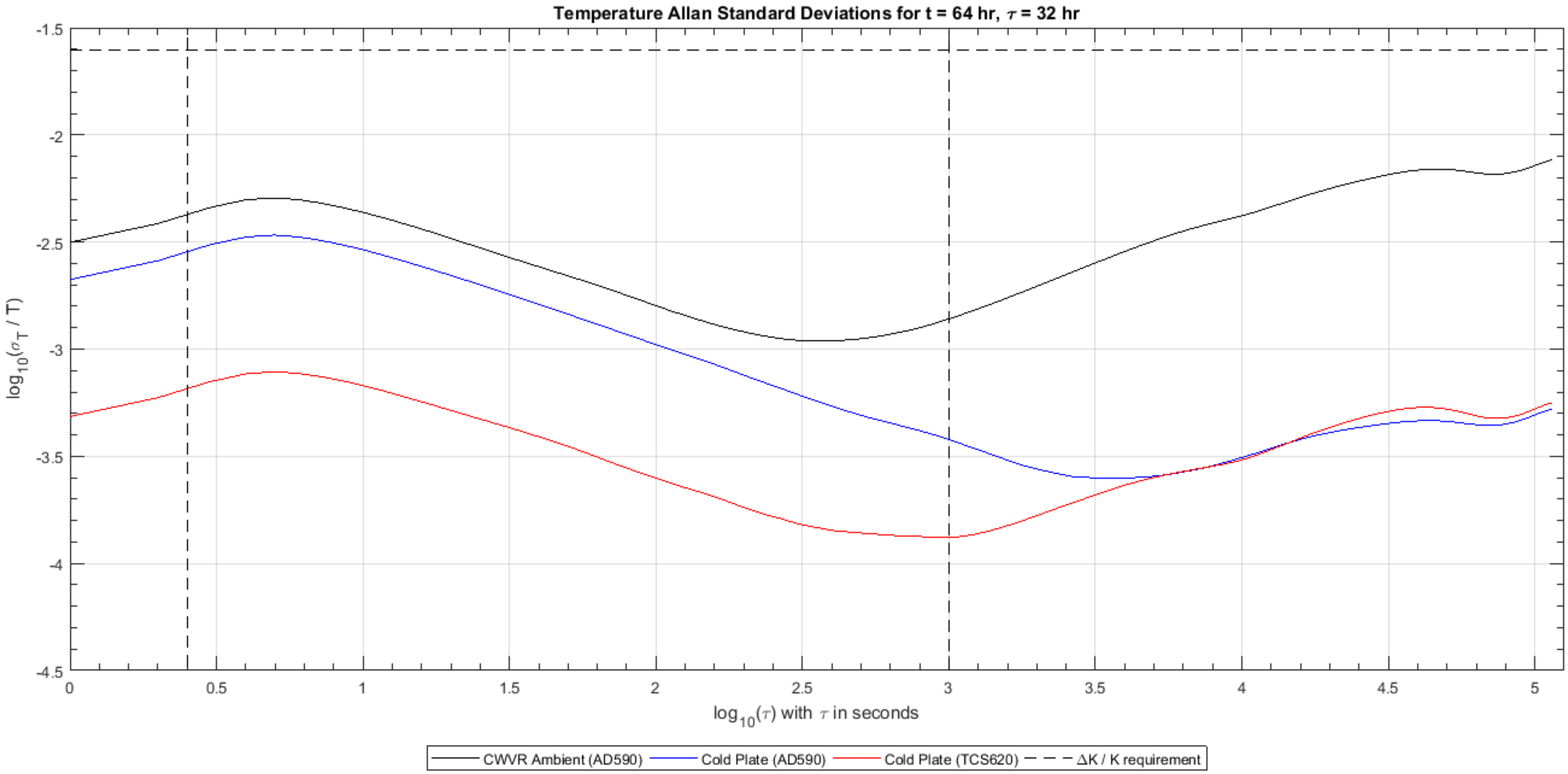
where IS_{xy} is leakage of x into y

IS_{12} (dB)	IS_{13} (dB)	IS_{14} (dB)	IS_{15} (dB)
-25.09	-30.79	-29.25	-32.38
IS_{21} (dB)	**IS_{23} (dB)**	**IS_{24} (dB)**	**IS_{25} (dB)**
-27.42	-22.90	-26.10	-27.72
IS_{31} (dB)	**IS_{32} (dB)**	**IS_{34} (dB)**	**IS_{35} (dB)**
-31.99	-21.78	-20.25	-25.46
IS_{41} (dB)	**IS_{42} (dB)**	**IS_{43} (dB)**	**IS_{45} (dB)**
-31.15	-25.67	-20.95	-22.74
IS_{51} (dB)	**IS_{52} (dB)**	**IS_{53} (dB)**	**IS_{54} (dB)**
-32.34	-25.35	-24.22	-20.81

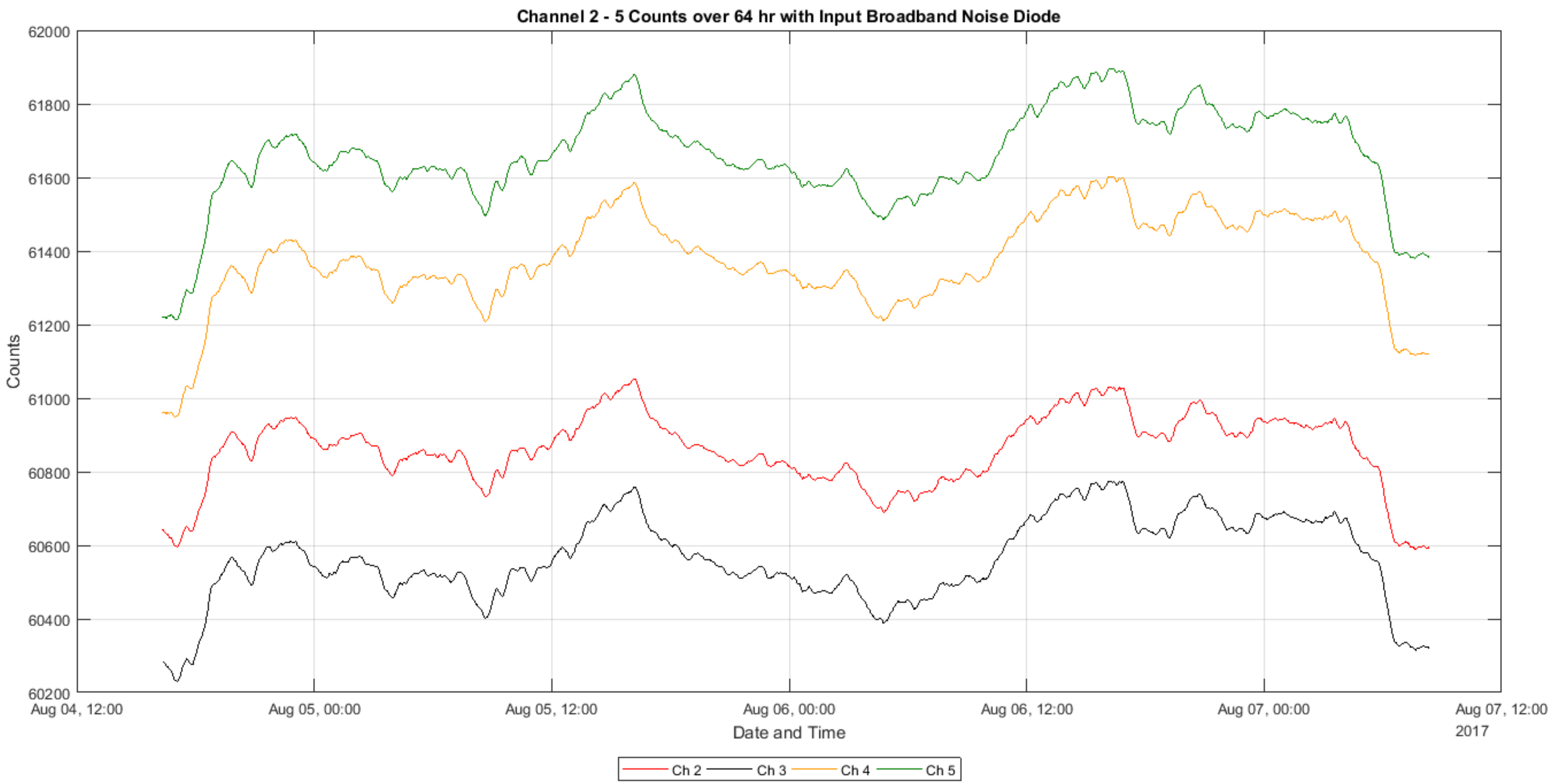


Single Channel Allan Standard Deviations for t = 105.4 min, τ = 52.7 min
-3.2
-3.3
-3.4
-3.5
-3.6
-3.7
-3.8
-3.9
-4
-4.1
log10(σPi / Pi)
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) with τ in seconds
log10(σP2 / P2)
log10(σP3 / P3)
log10(σP4 / P4)
log10(σP5 / P5)
Δg/g requirement over τshort,long

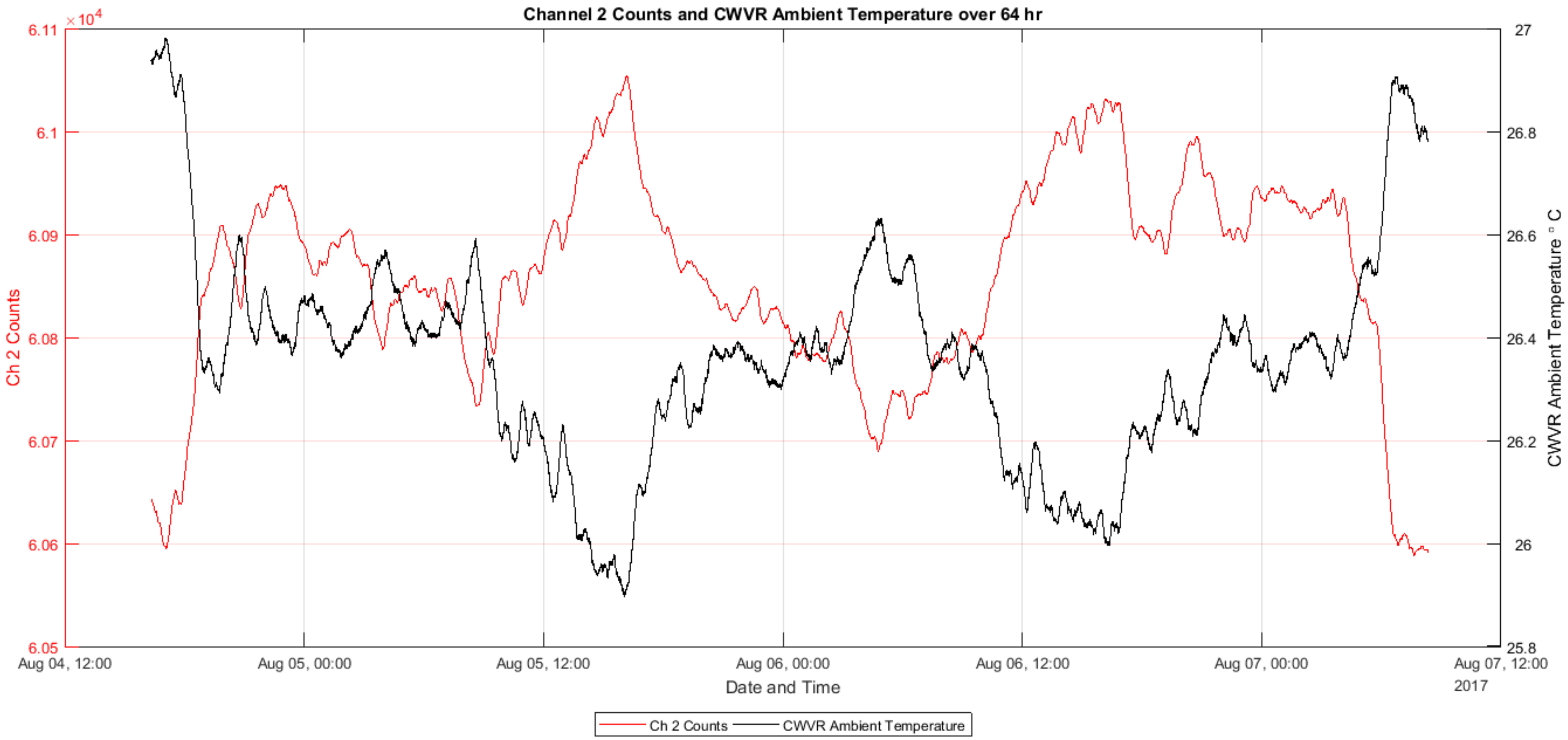

Allan Standard Deviation of ΔP_in for t = 105.4 min, τ = 52.7 min
-3
-3.5
-4
-4.5
log10(σ_ΔPin / ΔP_in)
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) with τ in seconds
log10(σ_ΔPin / ΔP_in)
Δg/g requirement over τ_short,long



Temperature Allan Standard Deviations for t = 64 hr, τ = 32 hr
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
log10(σT / T)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
log10(τ) with τ in seconds
CWVR Ambient (AD590)
Cold Plate (AD590)
Cold Plate (TCS620)
ΔK / K requirement

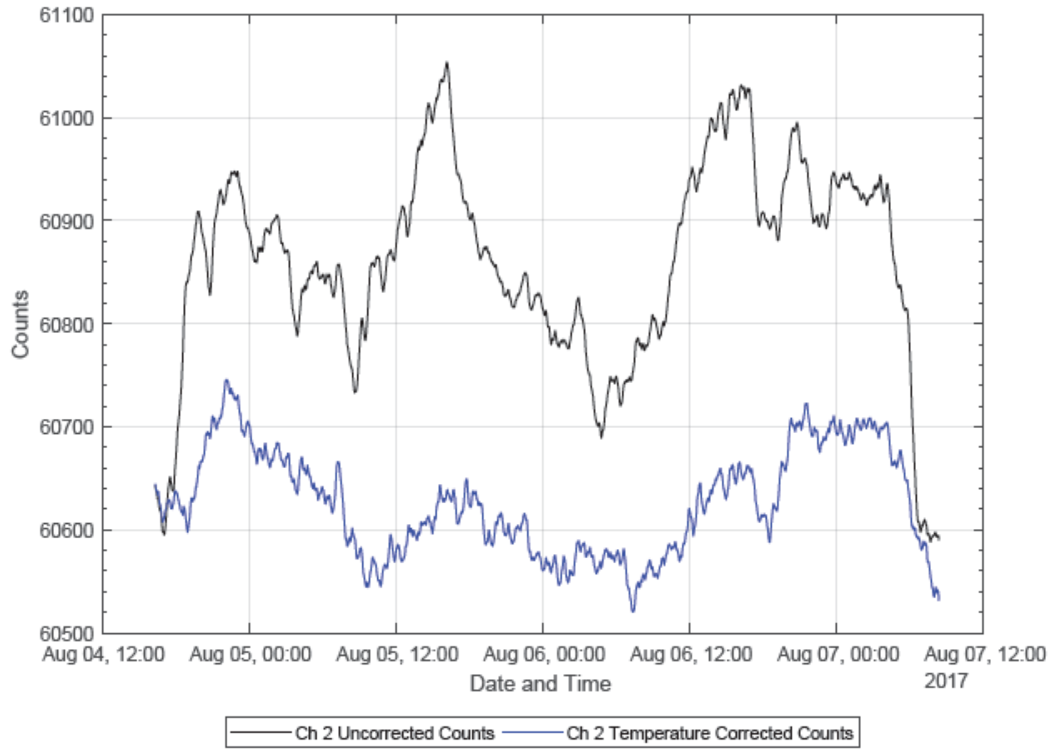


Channel 2 - 5 Counts over 64 hr with Input Broadband Noise Diode
62000
61800
61600
61400
61200
61000
60800
60600
60400
60200
Counts
Aug 04, 12:00
Aug 05, 00:00
Aug 05, 12:00
Aug 06, 00:00
Aug 06, 12:00
Aug 07, 00:00
Aug 07, 12:00
2017
Date and Time
Ch 2
Ch 3
Ch 4
Ch 5



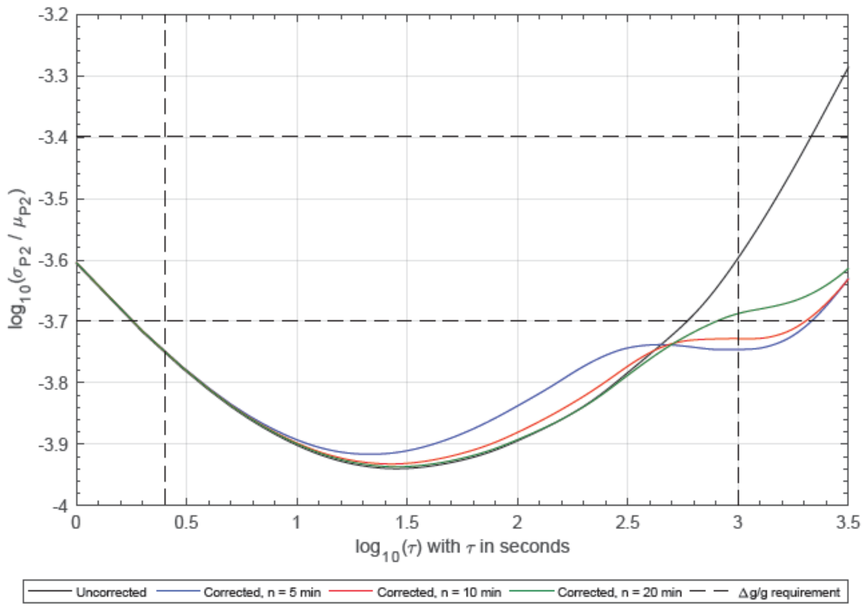
Channel 2 Counts and CWVR Ambient Temperature over 64 hr
×10^4
6.11
6.1
6.09
6.08
6.07
6.06
6.05
Ch 2 Counts
27
26.8
26.6
26.4
26.2
26
25.8
CWVR Ambient Temperature ° C
Aug 04, 12:00
Aug 05, 00:00
Aug 05, 12:00
Aug 06, 00:00
Aug 06, 12:00
Aug 07, 00:00
Aug 07, 12:00
2017
Date and Time
Ch 2 Counts
CWVR Ambient Temperature

Temperature Correction

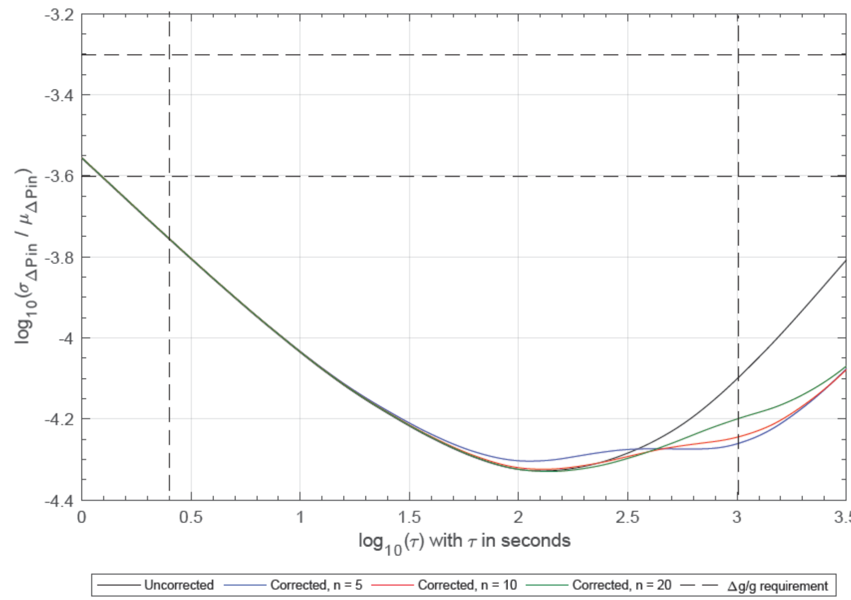


Stability with Temperature Correction

Single channel



Observable



Summary

- Phase fluctuations limit resolution and sensitivity
- CWVR prototype tested in lab
- Gain and temperature stability requirement met
- Channel isolation requirement met
- Correlation between temperature and gain
- Temperature correction improves stability
- EVLA Memo 203

Future

- Build and install four CWVRs for further on-sky testing
- Evaluate use of WVR for EVLA and ngVLA

References

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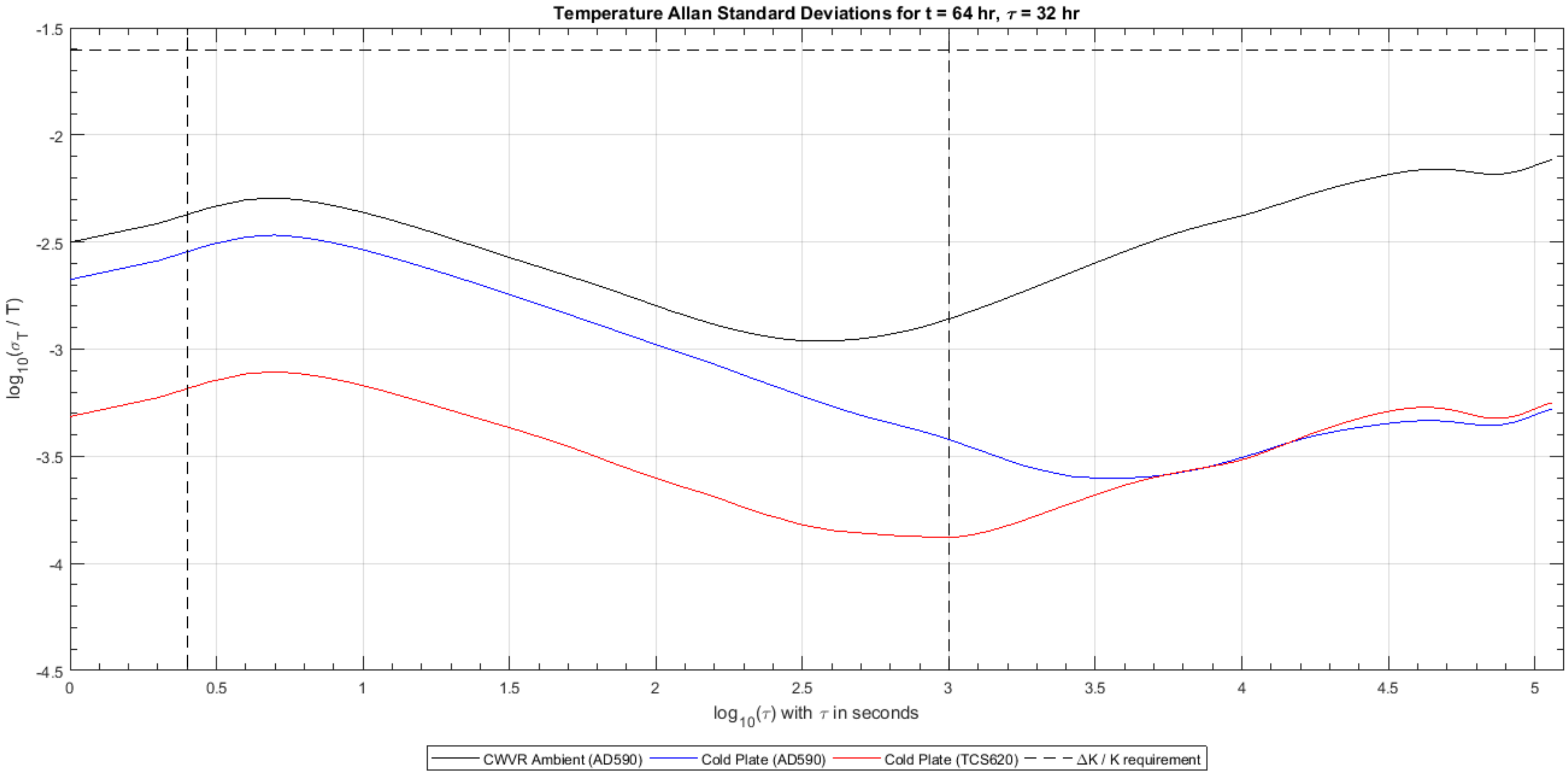
8. Thompson, A. R, Moran, J. M, Swenson Jr., G. W, *Interferometry and Synthesis in Radio Astronomy*, Second Edition, 2001, John Wiley & Sons.
9. Sutton, E. C., and Hueckstaedt, R. M., Radiometric monitoring of atmospheric water vapor as it pertains to phase correction in millimeter interferometry, Astron. Astrophys. Suppl. Ser., 119, 559-567, 1997.

Thank you.

Extra Slides


Temperature Allan Standard Deviations for t = 64 hr, τ = 32 hr
log10(σT / T)
log10(τ) with τ in seconds
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
CWVR Ambient (AD590)
Cold Plate (AD590)
Cold Plate (TCS620)
ΔK / K requirement

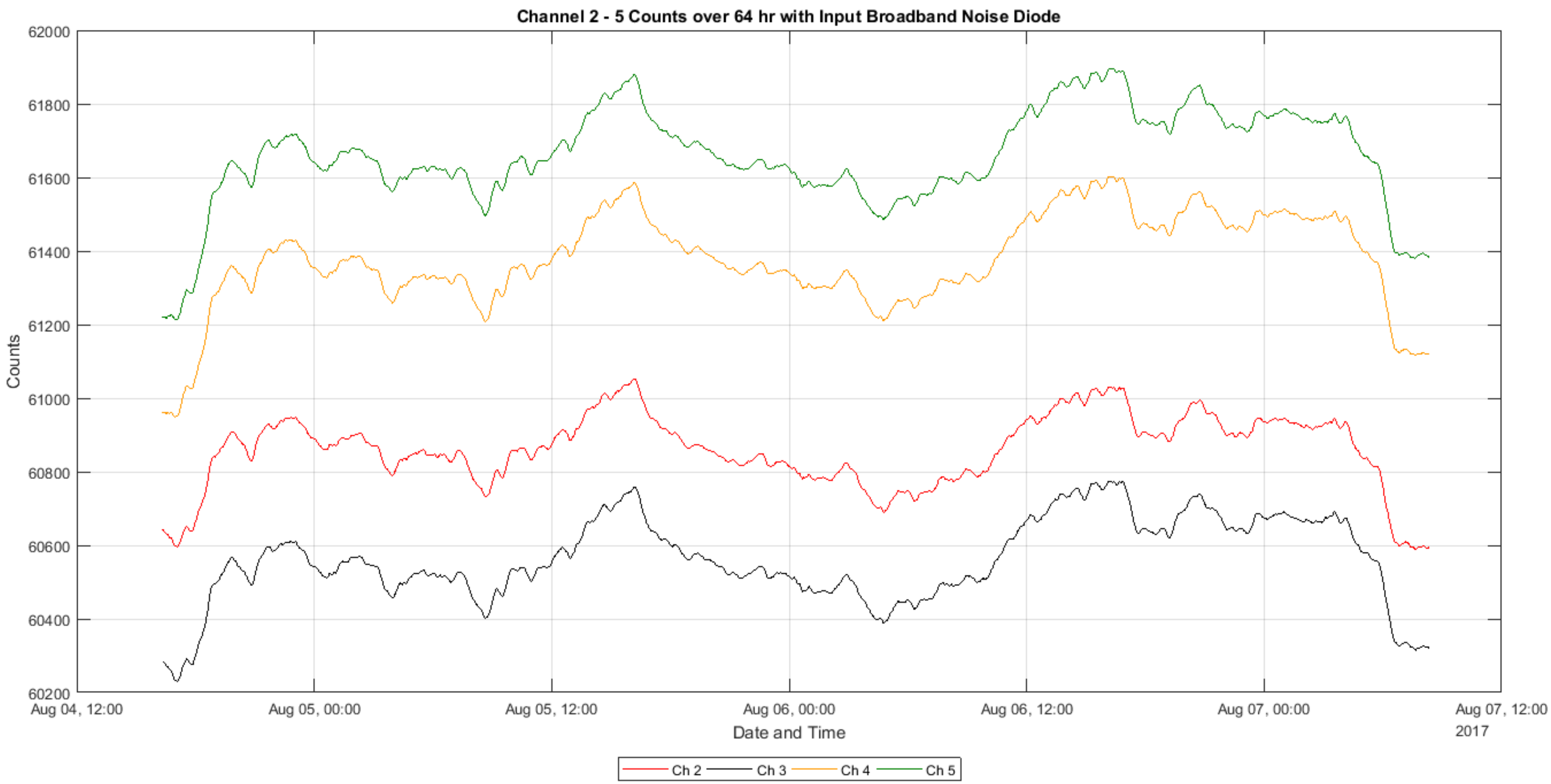
Allan Standard Deviations

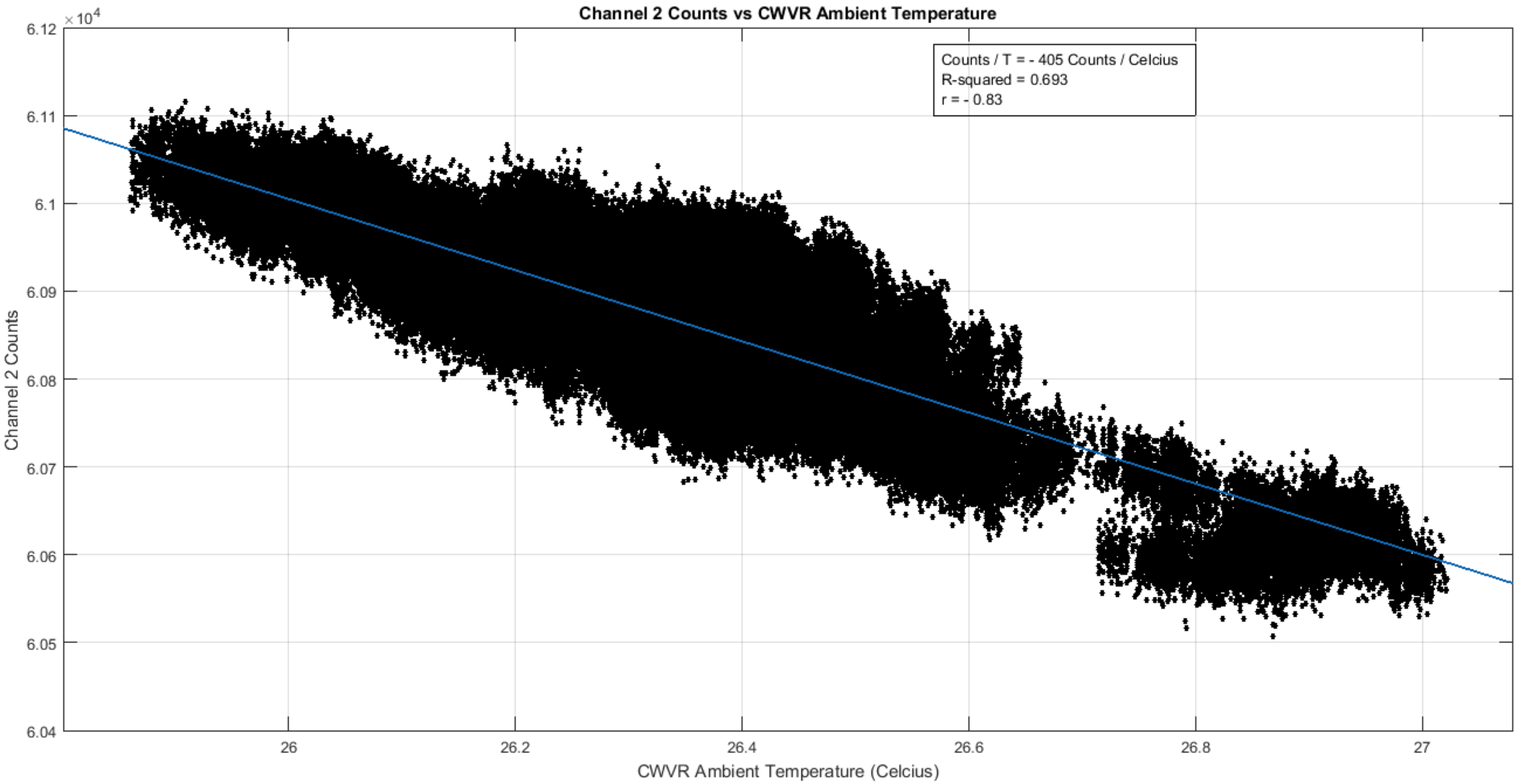
$$\sigma_P(\tau) = \left\{\frac{1}{2}\,\langle\{P(t) - P(t-\tau)\}^2\rangle\right\}^{\frac{1}{2}}$$

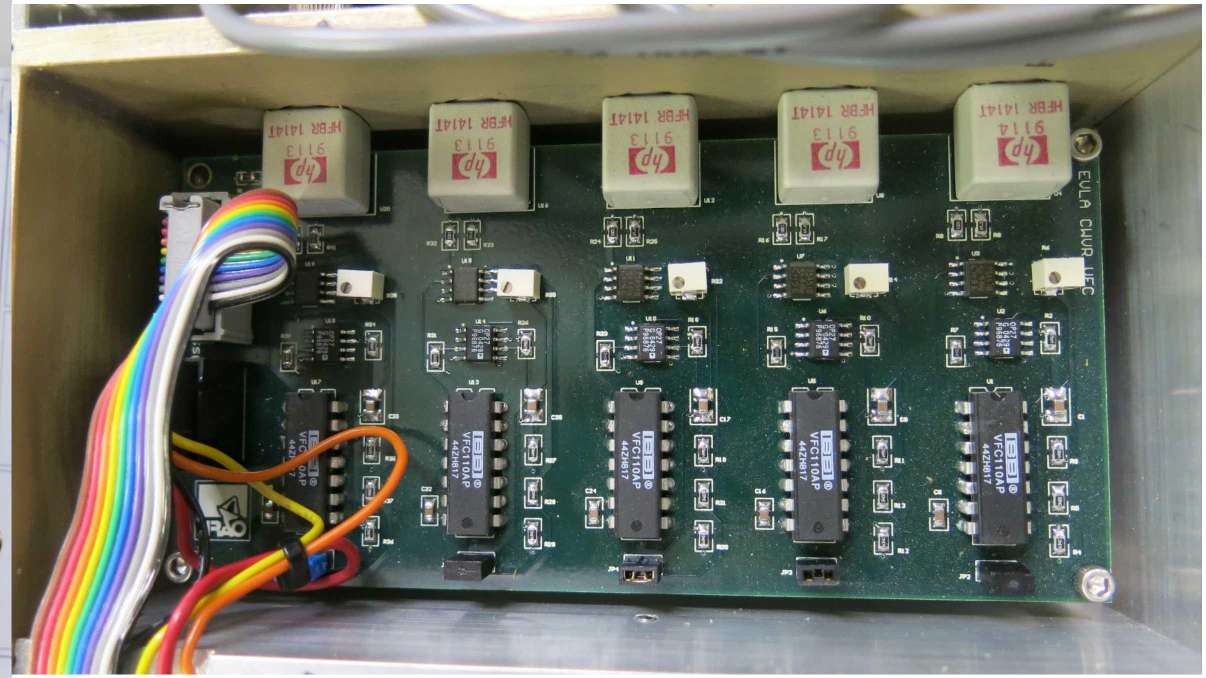
$$\sigma_P(\tau) = \left\{\frac{1}{2}\sum_{j=1}^{N/2}\frac{1}{N-\tau_j}\sum_{i=1}^{N-\tau_j}\left[P\left(t_i+\tau_j\right) - P(t_i)\right]^2\right\}^{\frac{1}{2}} \quad and\ \mu_{norm} = \langle P(t)\rangle$$

$$\sigma_{P_x - P_y}(\tau) = \left\{\frac{1}{2}\sum_{j=1}^{N/2}\frac{1}{N-\tau_j}\sum_{i=1}^{N-\tau_j}\left\{\left[P_x\left(t_i+\tau_j\right) - P_y\left(t_i+\tau_j\right)\right] - \left[P_x(t_i) - P_y(t_i)\right]\right\}^2\right\}^{\frac{1}{2}} and\ \mu_{norm} = \frac{\langle P_x(t) + P_y(t)\rangle}{2}$$

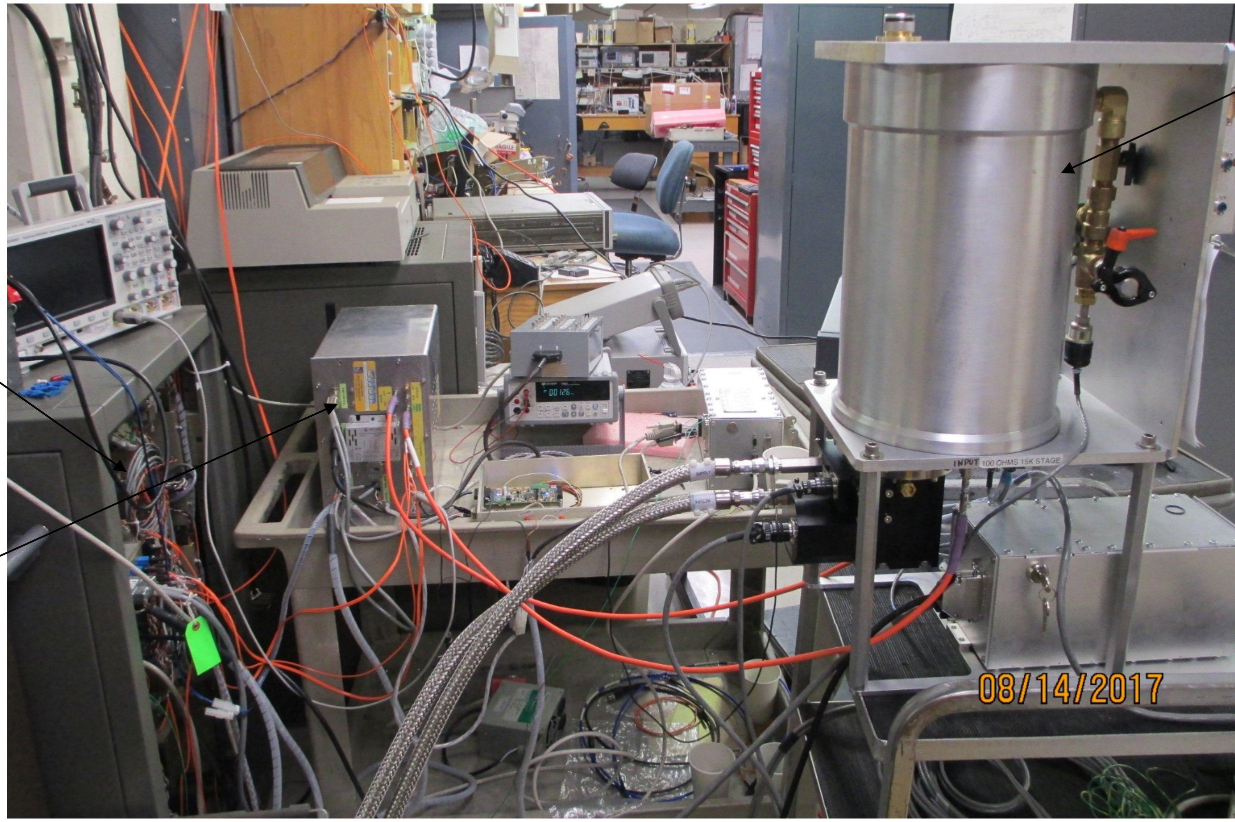
$$\sigma_{\Delta P_{in}}(\tau) = \left\{\frac{1}{2}\sum_{j=1}^{N/2}\frac{1}{N-\tau_j}\sum_{i=1}^{N-\tau_j}\left\{\sum_{k=1}^{5} w_k P_k\left(t_i+\tau_j\right) - \sum_{k=1}^{5} w_k P_k(t_i)\right\}^2\right\}^{\frac{1}{2}} and\ \mu_{norm} = \frac{\langle P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t)\rangle}{5}$$


Channel 2 - 5 Counts over 64 hr with Input Broadband Noise Diode
62000
61800
61600
61400
61200
61000
60800
60600
60400
60200
Counts
Aug 04, 12:00
Aug 05, 00:00
Aug 05, 12:00
Aug 06, 00:00
Aug 06, 12:00
Aug 07, 00:00
Aug 07, 12:00
2017
Date and Time
Ch 2
Ch 3
Ch 4
Ch 5


Channel 2 Counts vs CWVR Ambient Temperature
Counts / T = - 405 Counts / Celcius
R-squared = 0.693
r = - 0.83
×10^4
6.12
6.11
6.1
6.09
6.08
6.07
6.06
6.05
6.04
Channel 2 Counts
26
26.2
26.4
26.6
26.8
27
CWVR Ambient Temperature (Celcius)



Instrument Setup



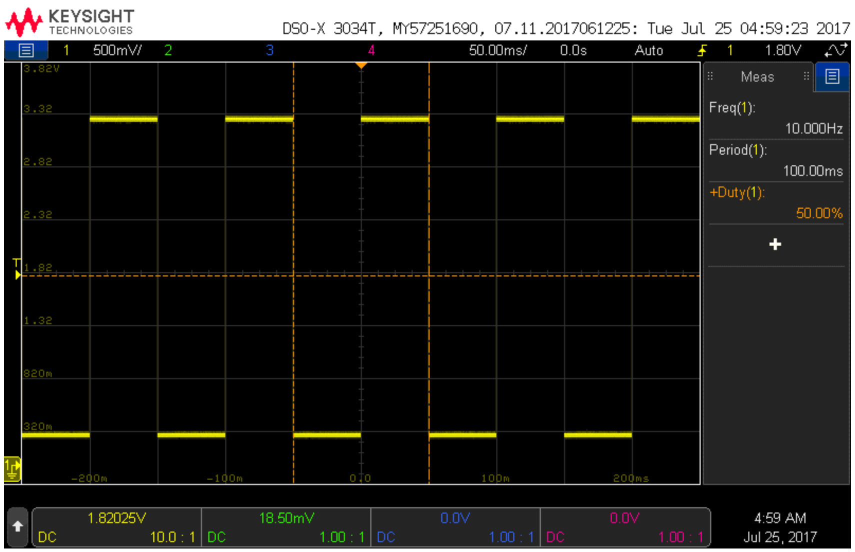
F318

CWVR

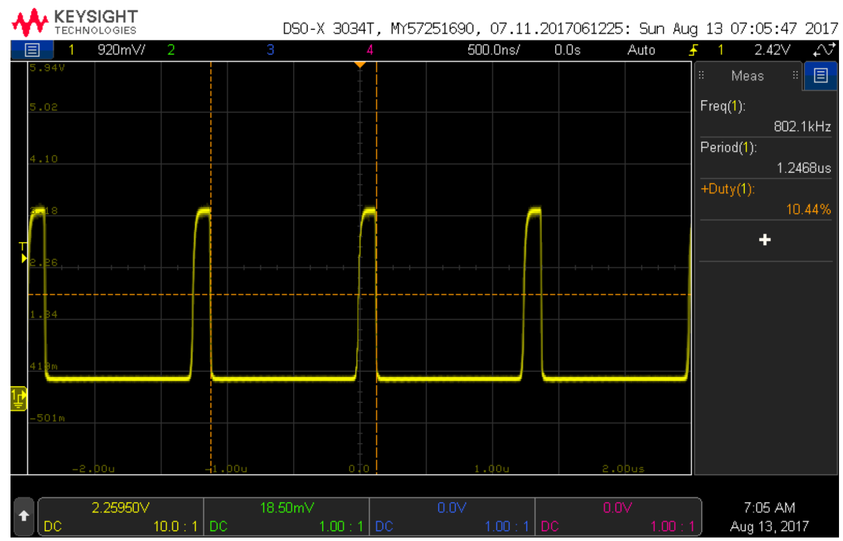
Dewar

Voltage – Frequency Converter

10 Hz Calibration Signal



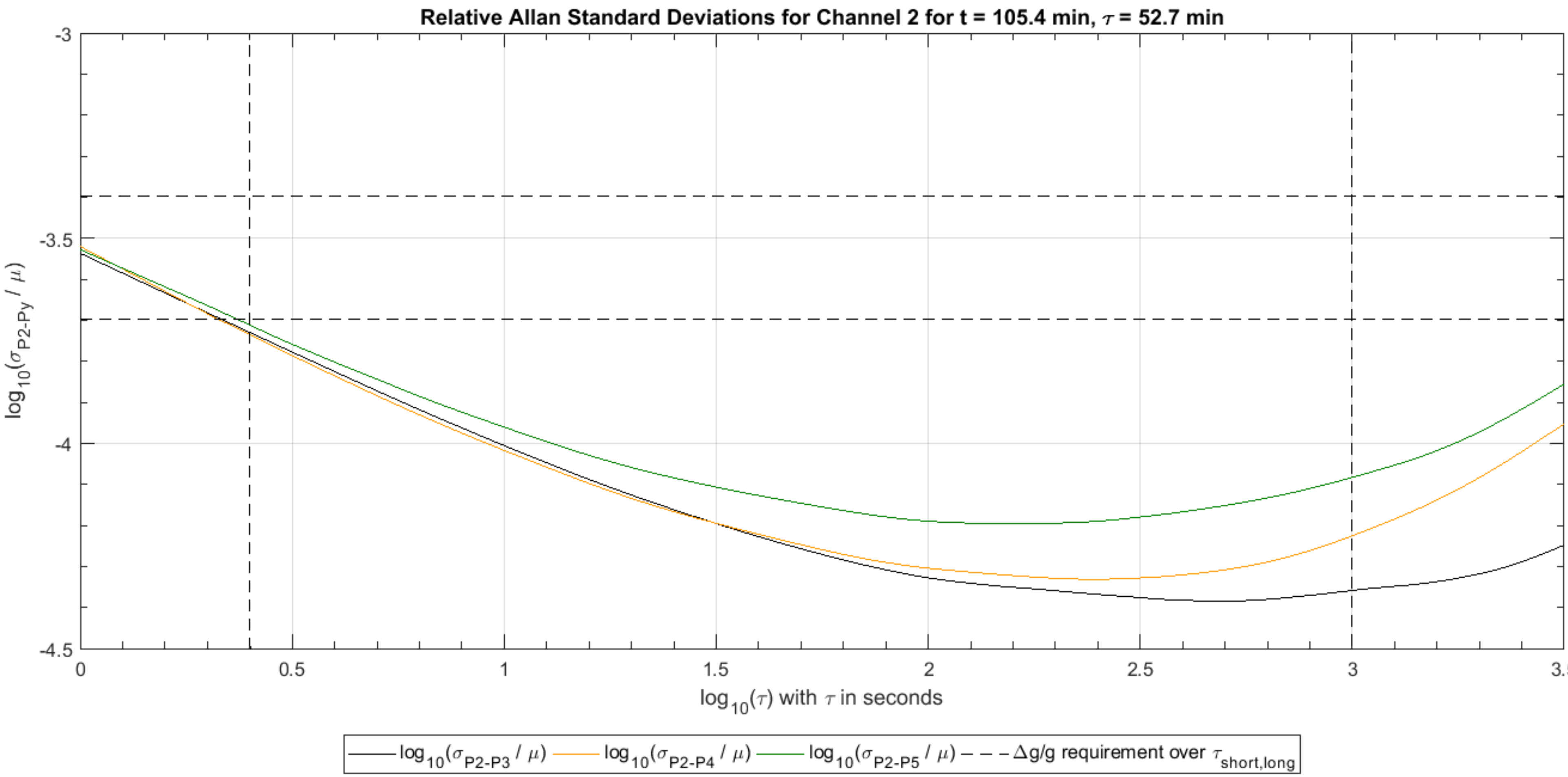
V-F Board Frequency Output

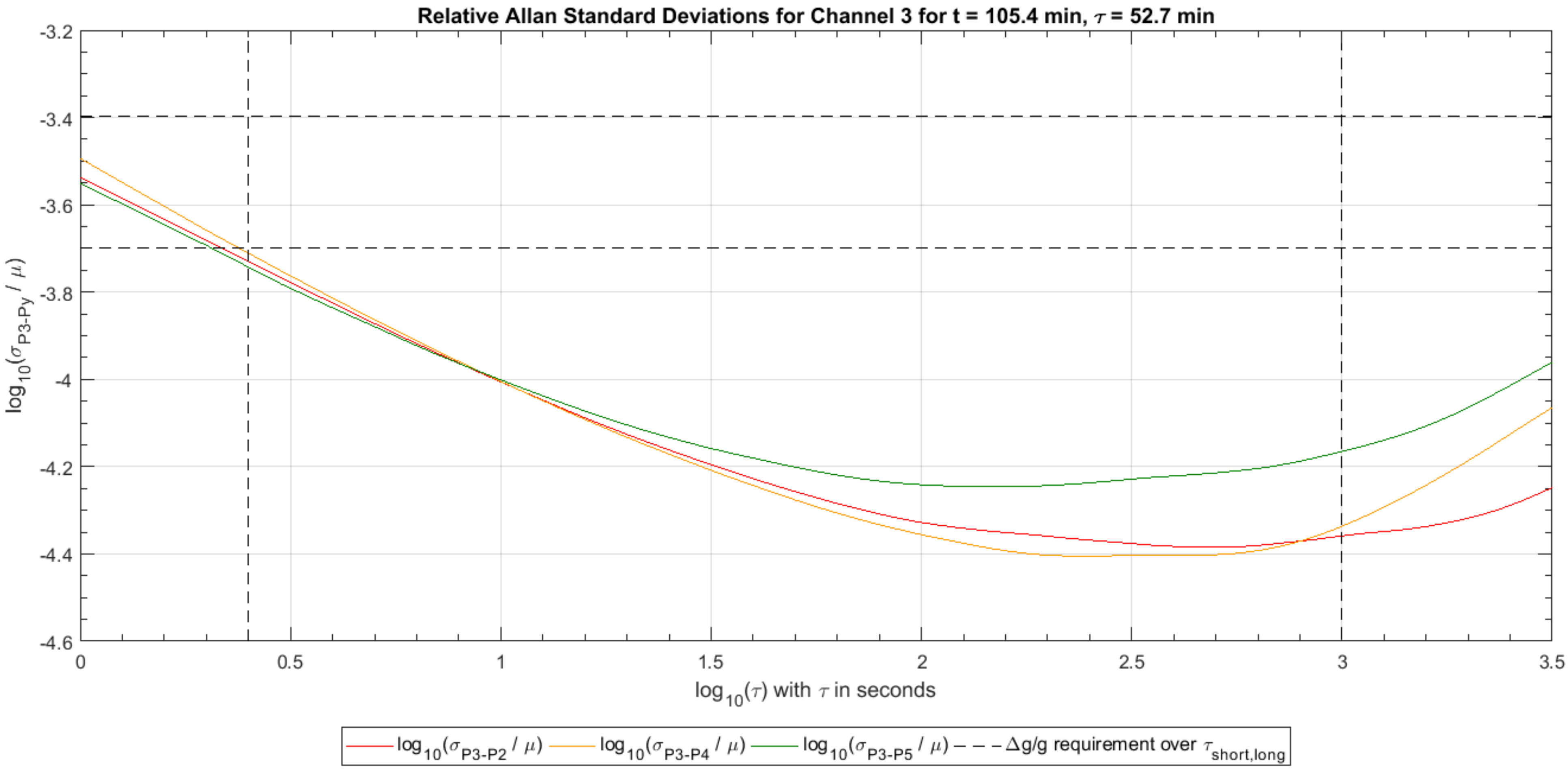


$$V_{out} = 0 - 10\ \text{V} \longleftrightarrow \nu_{out} = 0 - 2\ \text{MHz}$$

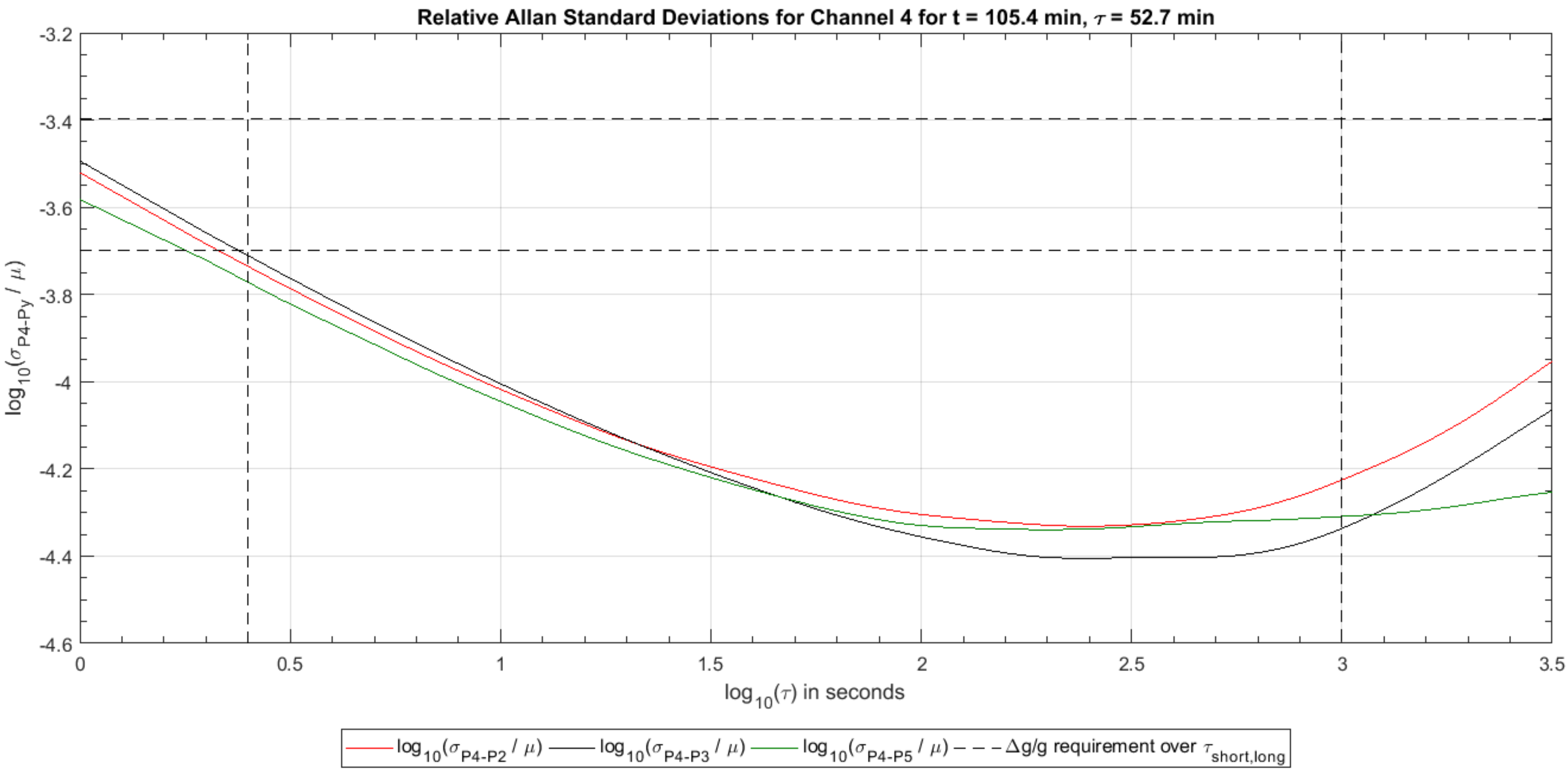
$$\text{Ch1}_{\text{Low,High}} = \frac{802.1 \times 10^3\ \text{cycles}}{\text{sec}} \times 50\ \text{ms} \times \frac{1\ \text{sec}}{10^3\ \text{ms}} \sim 40{,}000\ \text{cycles or counts}$$

$$\text{Ch1}_{\text{Total}} = \text{Ch1}_{\text{Low}} + \text{Ch1}_{\text{High}} \sim 80{,}000\ \text{cycles or counts}$$

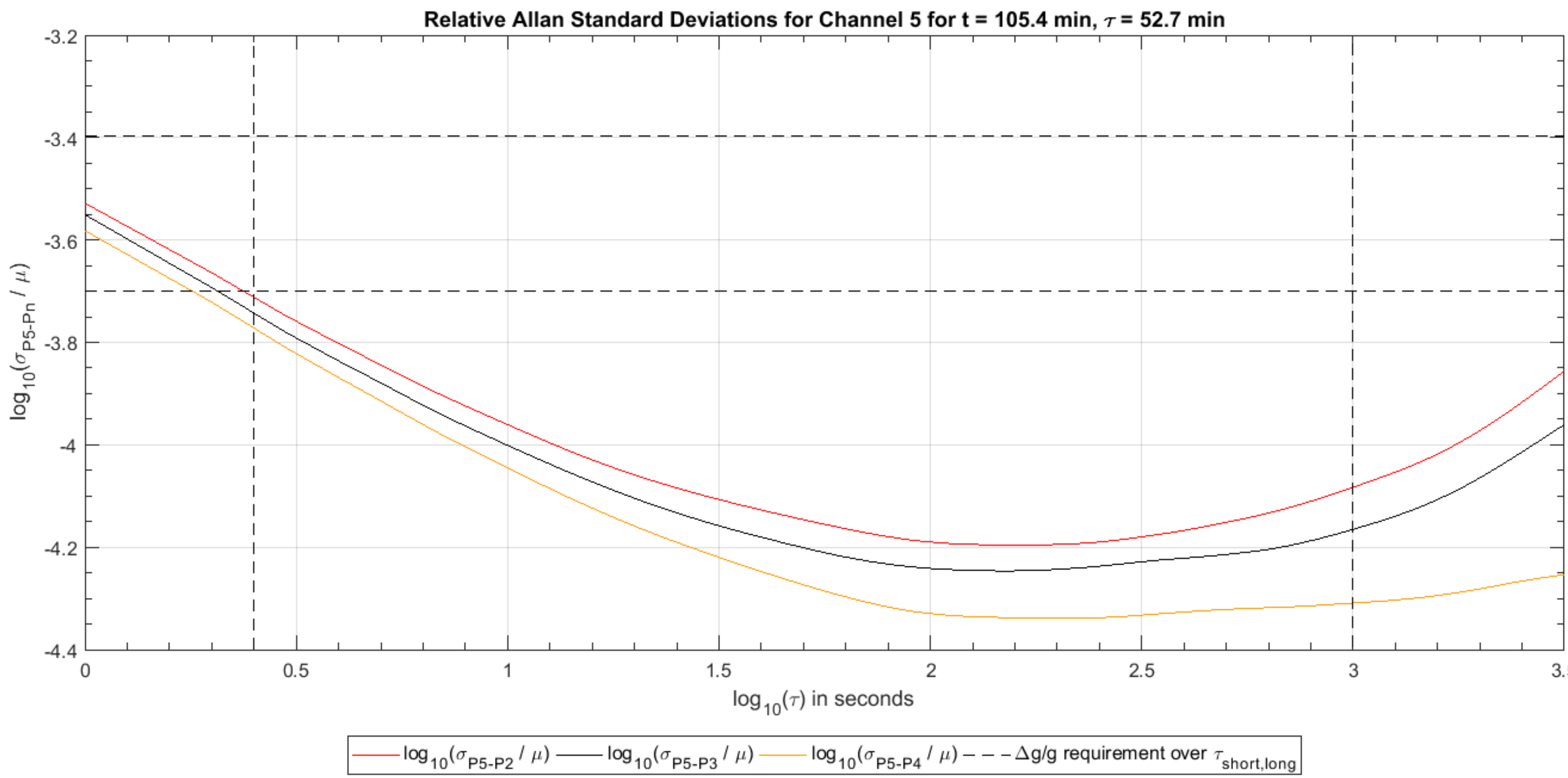

Relative Allan Standard Deviations for Channel 2 for t = 105.4 min, τ = 52.7 min
-3
-3.5
-4
-4.5
log10(σP2-Py / μ)
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) with τ in seconds
log10(σP2-P3 / μ)
log10(σP2-P4 / μ)
log10(σP2-P5 / μ)
Δg/g requirement over τshort,long

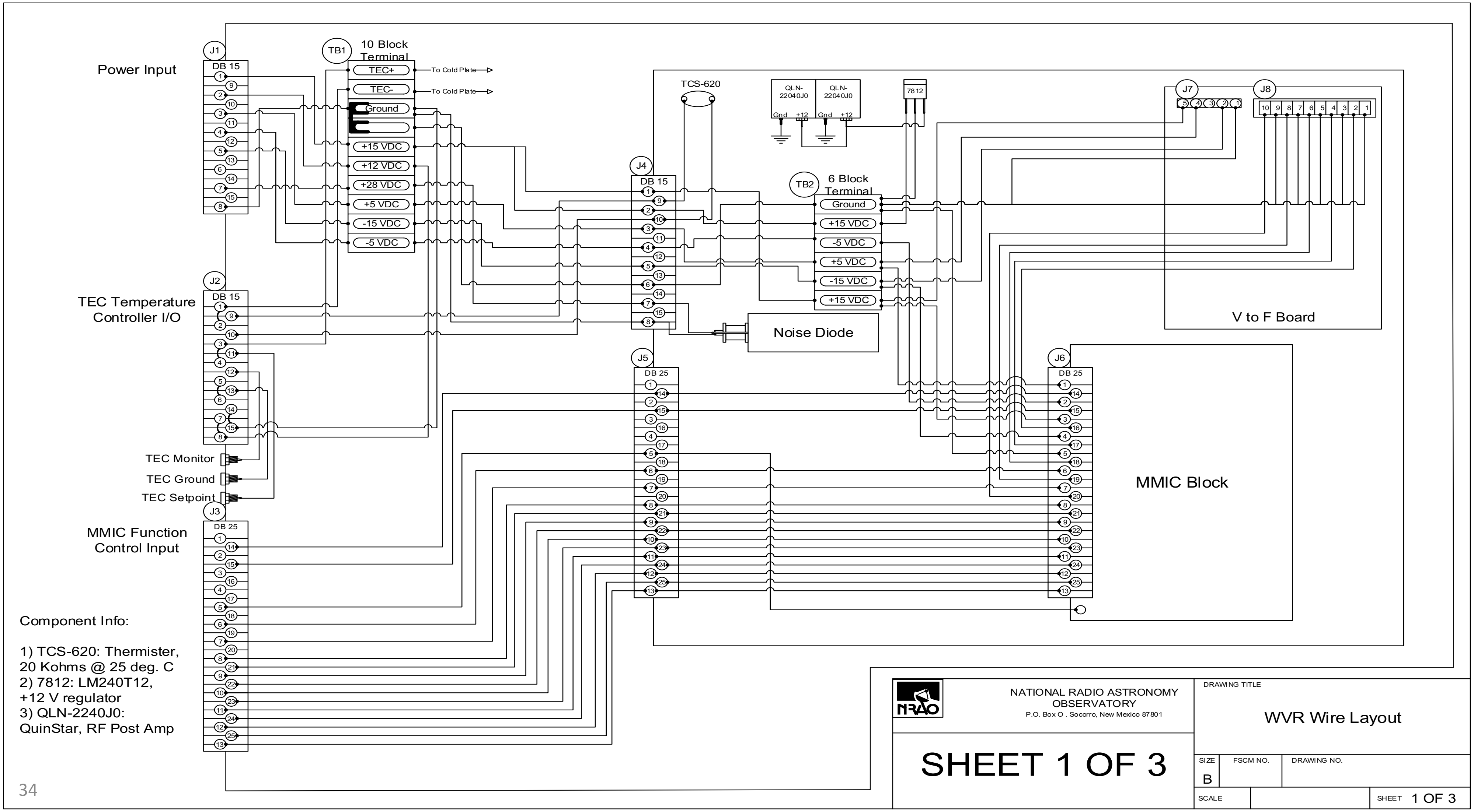


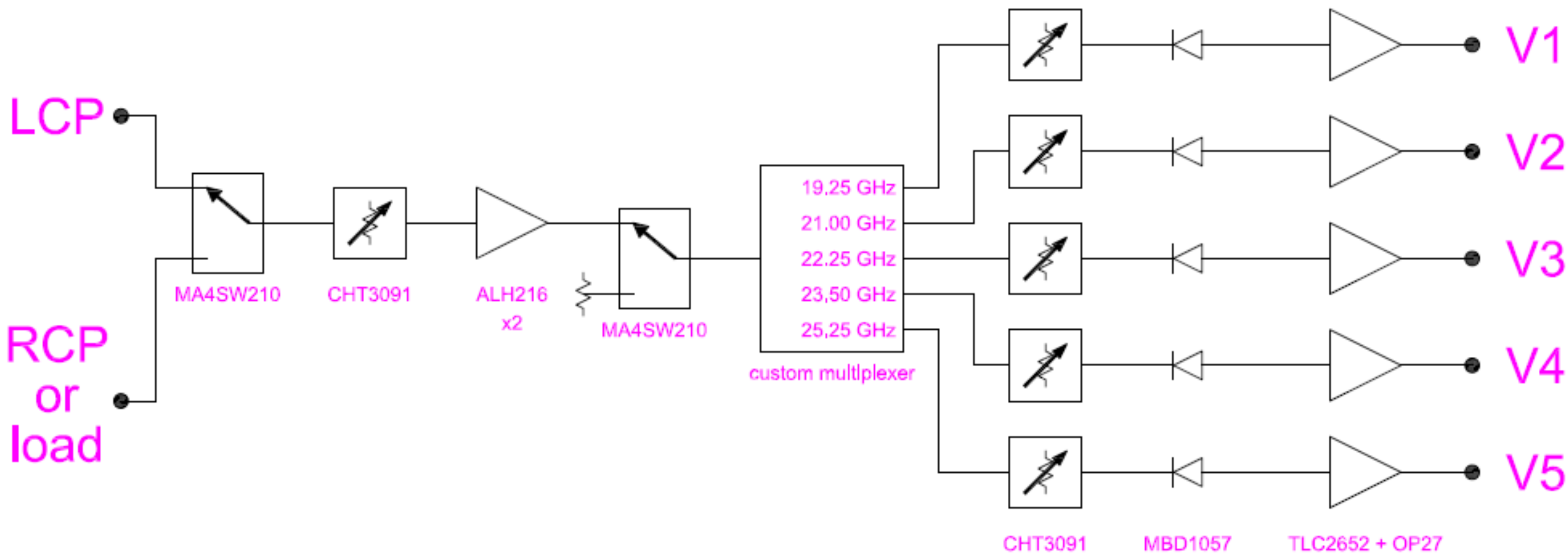
Relative Allan Standard Deviations for Channel 3 for t = 105.4 min, τ = 52.7 min
log10(σP3-Py / μ)
-3.2
-3.4
-3.6
-3.8
-4
-4.2
-4.4
-4.6
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) with τ in seconds
log10(σP3-P2 / μ)
log10(σP3-P4 / μ)
log10(σP3-P5 / μ)
Δg/g requirement over τshort,long



Relative Allan Standard Deviations for Channel 4 for t = 105.4 min, τ = 52.7 min
-3.2
-3.4
-3.6
-3.8
-4
-4.2
-4.4
-4.6
log10(σP4-Py / μ)
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) in seconds
log10(σP4-P2 / μ)
log10(σP4-P3 / μ)
log10(σP4-P5 / μ)
Δg/g requirement over τshort,long


Relative Allan Standard Deviations for Channel 5 for t = 105.4 min, τ = 52.7 min
-3.2
-3.4
-3.6
-3.8
-4
-4.2
-4.4
log10(σP5-Pn / μ)
0
0.5
1
1.5
2
2.5
3
3.5
log10(τ) in seconds
log10(σP5-P2 / μ)
log10(σP5-P3 / μ)
log10(σP5-P4 / μ)
Δg/g requirement over τshort,long


Power Input
J1
DB 15
TB1
10 Block Terminal
TEC+
TEC-
Ground
+15 VDC
+12 VDC
+28 VDC
+5 VDC
-15 VDC
-5 VDC
To Cold Plate
To Cold Plate
TEC Temperature Controller I/O
J2
DB 15
TEC Monitor
TEC Ground
TEC Setpoint
MMIC Function Control Input
J3
DB 25
TCS-620
QLN-22040J0
QLN-22040J0
Gnd
+12
7812
J4
DB 15
TB2
6 Block Terminal
Ground
+15 VDC
-5 VDC
+5 VDC
-15 VDC
+15 VDC
Noise Diode
J5
DB 25
J6
DB 25
MMIC Block
J7
J8
V to F Board
Component Info:
1) TCS-620: Thermister, 20 Kohms @ 25 deg. C
2) 7812: LM240T12, +12 V regulator
3) QLN-2240J0: QuinStar, RF Post Amp
NATIONAL RADIO ASTRONOMY OBSERVATORY
P.O. Box O . Socorro, New Mexico 87801
DRAWING TITLE
WVR Wire Layout
SHEET 1 OF 3
SIZE
B
FSCM NO.
DRAWING NO.
SCALE
SHEET 1 OF 3

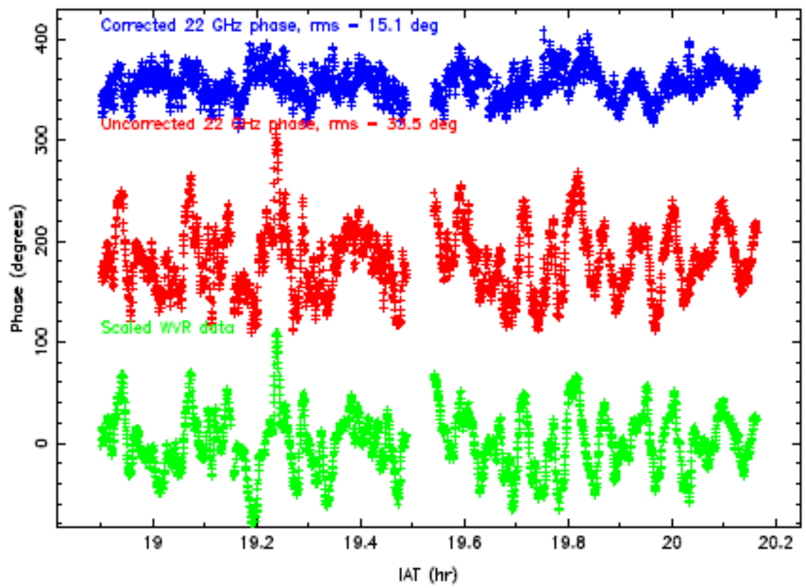


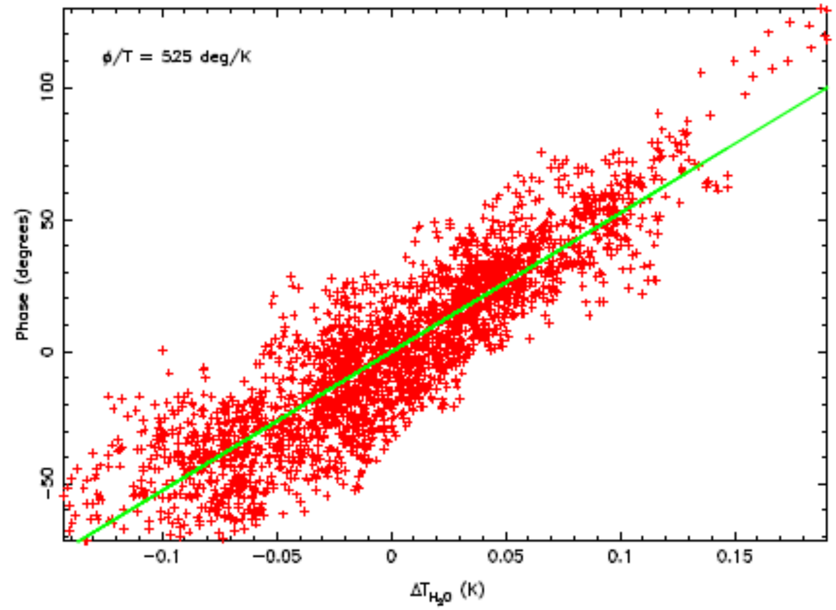
LCP
RCP or load
MA4SW210
CHT3091
ALH216 x2
MA4SW210
19.25 GHz
21.00 GHz
22.25 GHz
23.50 GHz
25.25 GHz
custom multiplexer
CHT3091
MBD1057
TLC2652 + OP27
V1
V2
V3
V4
V5

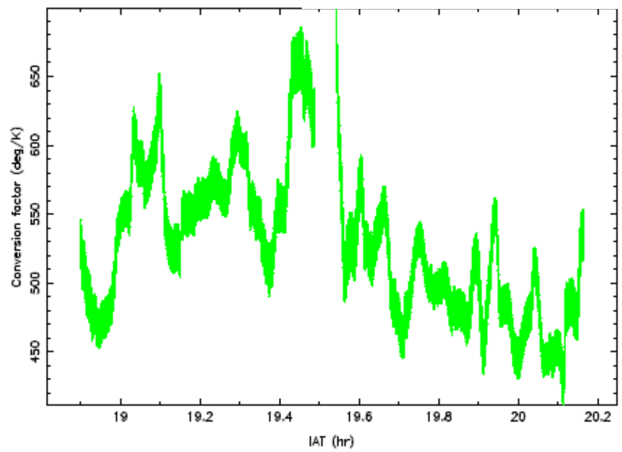
- Gain Stability Requirements (5 Channels)
  - $\Delta T \propto \Delta P_{in} = w_1P_1 + w_2P_2 + w_3P_3 + w_4P_4 + w_5P_5$
  - $w_1 = 0.25$, $w_2 = -0.5$, $w_3 = 1$, $w_4 = -0.5$, $w_5 = 0.25$
  - ~ 35 μm of WV ⟶ 220 μm of electrical path delay (λ/30 for λ = 7 mm)
  - For ΔT_{rms} ~ 25 mK, $T_{i,rms}$ ~ 19.612 mK
  - For T_{sys} = 50 – 100 K, τ = 2.5 - 10^3 seconds
  - **$\Delta g / g \sim 2.5 – 5 \times 10^{-4}$** (Observable)   **$\Delta g_i / g_i \sim 1.96 – 3.92 \times 10^{-4}$** (Individual Channel)
- Channel Isolation Requirements (5 Channels)
  - **~ - 20 dB**
  - ~ 1% power leakage between any two channels

Chandler et al (2005), Butler (1999)

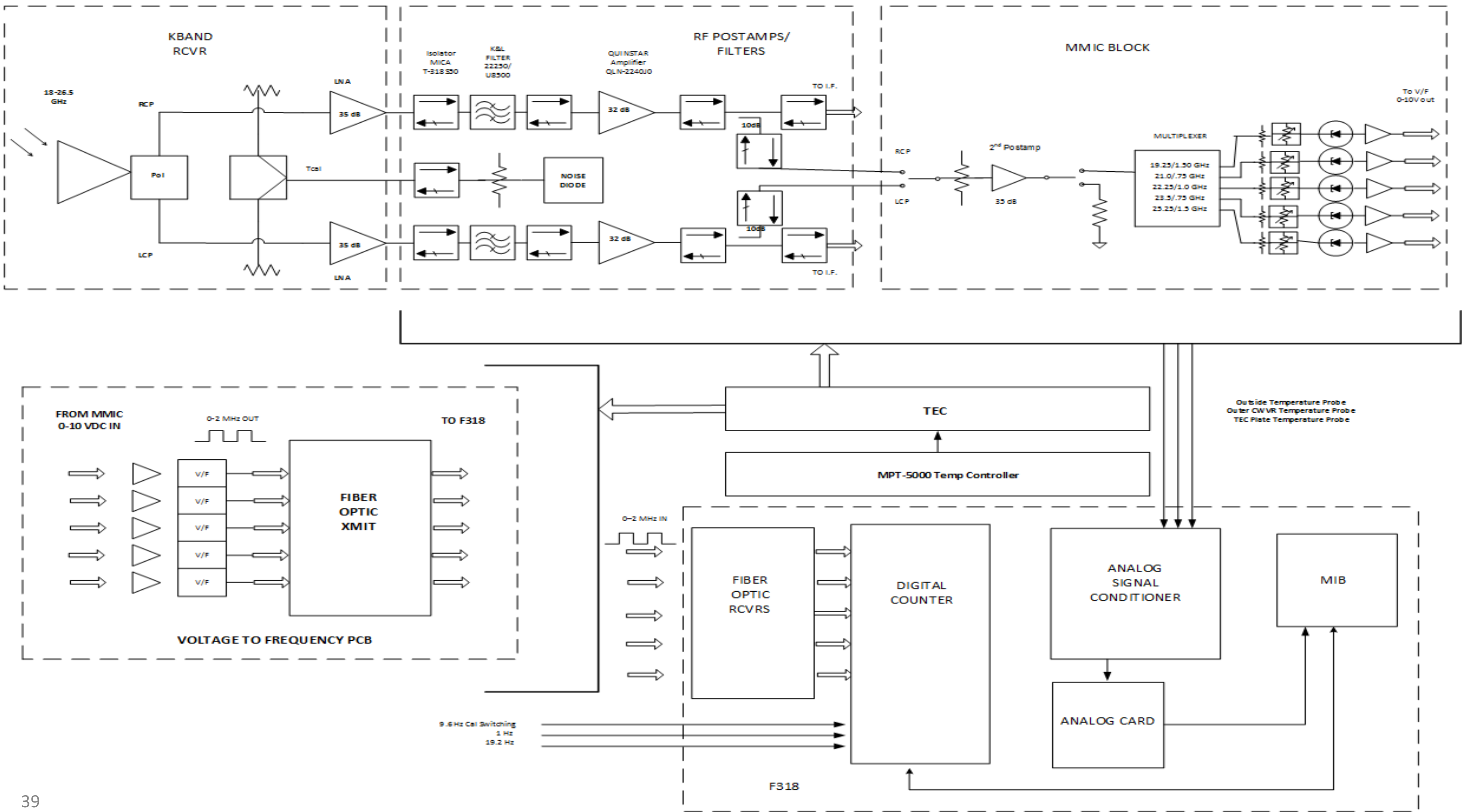
	ν (low) (GHz)	ν (center) (GHz)	ν (high) (GHz)	Δν (GHz)
Ch1	18.5	19.25	20	1.5
Ch2	20.625	21	21.375	0.75
Ch3	21.75	22.25	22.75	1
Ch4	23.125	23.5	23.875	0.75
Ch5	24.5	25.25	26	1.5



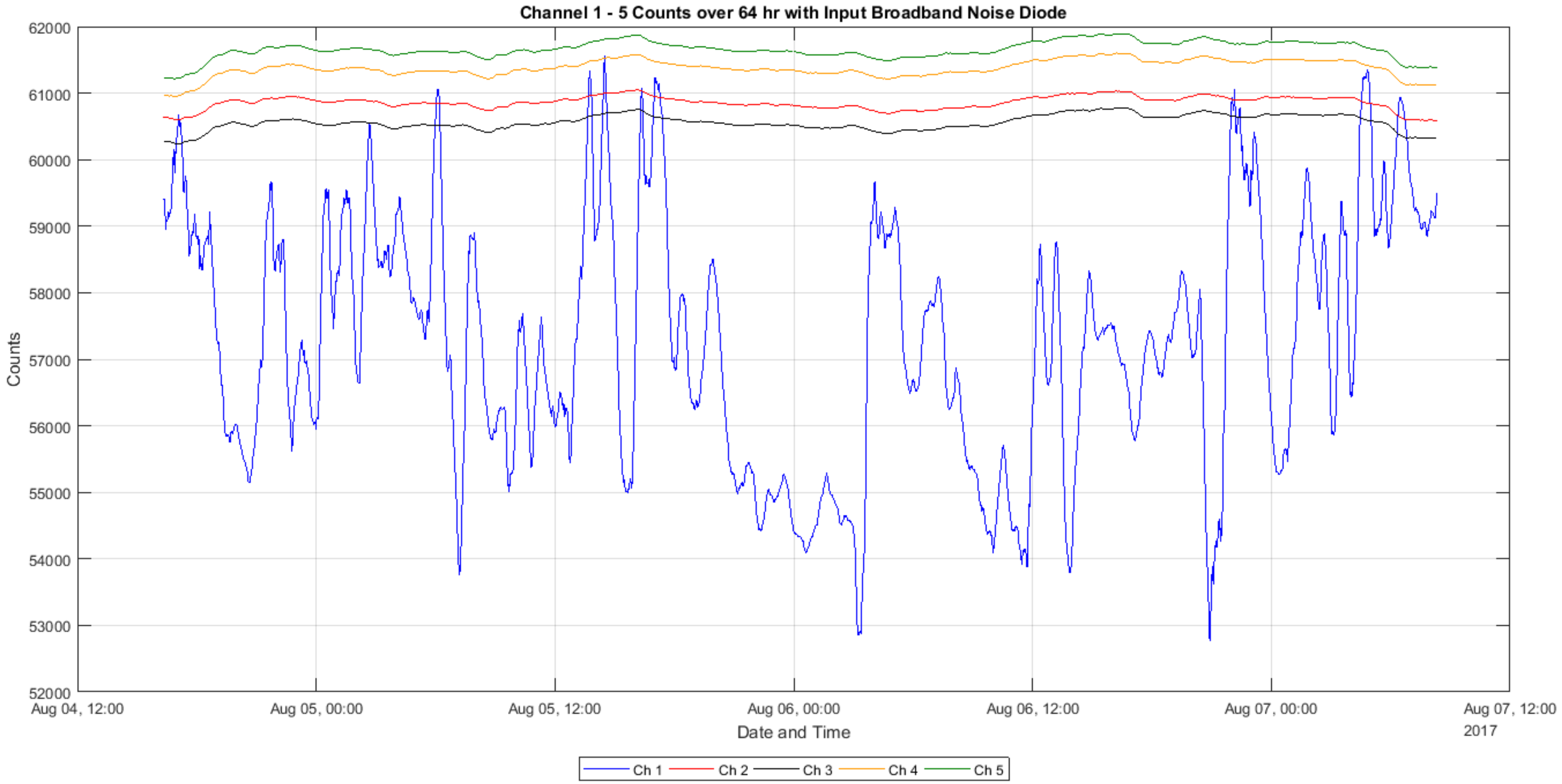


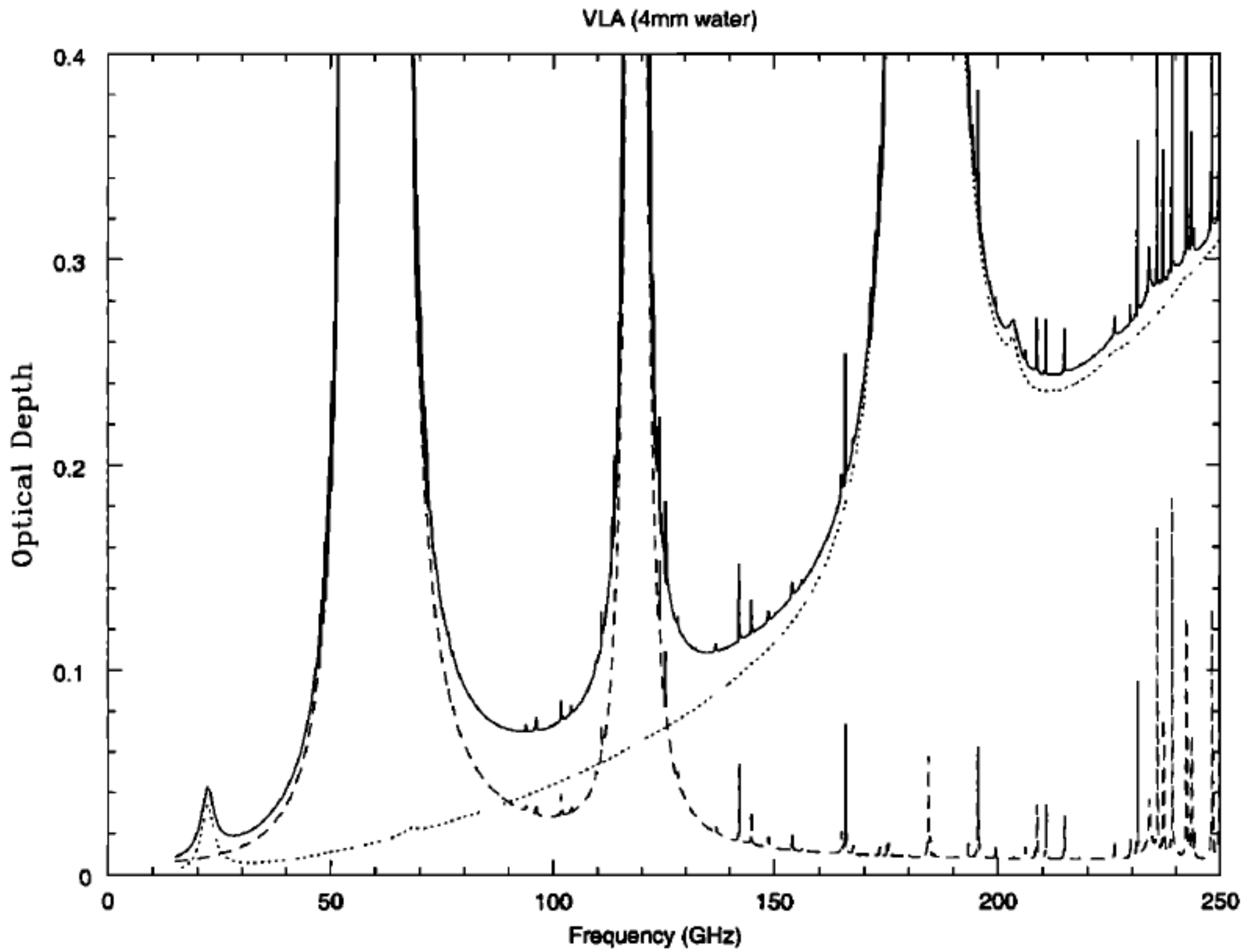


Chandler et al (2004)



KBAND
RCVR
18-26.5
GHz
RCP
LCP
Pol
Tcal
LNA
35 dB
35 dB
LNA
RF POSTAMPS/
FILTERS
Isolator
MICA
T-318S30
K&L
FILTER
22250/
U8500
QUINSTAR
Amplifier
QLN-2240J0
32 dB
32 dB
NOISE
DIODE
10dB
10dB
TO I.F.
TO I.F.
MMIC BLOCK
RCP
LCP
2nd Postamp
35 dB
MULTIPLEXER
19.25/1.50 GHz
21.0/.75 GHz
22.25/1.0 GHz
23.5/.75 GHz
25.25/1.5 GHz
To V/F
0-10V out
FROM MMIC
0-10 VDC IN
0-2 MHz OUT
TO F318
V/F
V/F
V/F
V/F
V/F
FIBER
OPTIC
XMIT
VOLTAGE TO FREQUENCY PCB
TEC
MPT-5000 Temp Controller
Outside Temperature Probe
Outer CWVR Temperature Probe
TEC Plate Temperature Probe
0–2 MHz IN
FIBER
OPTIC
RCVRS
DIGITAL
COUNTER
ANALOG
SIGNAL
CONDITIONER
MIB
ANALOG CARD
9.6 Hz Cal Switching
1 Hz
19.2 Hz
F318


Channel 1 - 5 Counts over 64 hr with Input Broadband Noise Diode
Counts
62000
61000
60000
59000
58000
57000
56000
55000
54000
53000
52000
Aug 04, 12:00
Aug 05, 00:00
Aug 05, 12:00
Aug 06, 00:00
Aug 06, 12:00
Aug 07, 00:00
Aug 07, 12:00
2017
Date and Time
Ch 1
Ch 2
Ch 3
Ch 4
Ch 5



Carilli & Holdaway (1999)

$$Count_{corr,i} = \begin{cases} Count_i & for\ i = 1, 2, 3, ..., n \\ Count_i - A(T_{sm,i} - T_{ave}) & for\ i = n+1, n+2, ..., N \end{cases} \tag{23}$$

$$T_{ave} = \frac{1}{n} \sum_{i=1}^{n} T_i \tag{24}$$

$$T_{sm,i} = \frac{1}{n} \sum_{j=i-n}^{i} T_j \tag{25}$$

where A = -405, $Count_{corr,i}$ is the temperature corrected count at point i, $Count_i$ is the measured count at point i, T_{ave} is the mean of the CWVR ambient temperature for the first n seconds of a N-second total observation time, $T_{sm,i}$ is the temperature at point i taken as the mean from the preceding n seconds to point i, and T_j is

AD590 (Box Ambient)

AD590, TCS620 (Cold Plate)