

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note	LIGO-T2600158-vX	2026/08/01
Validating LIGO Interferometer Models		
Abhiram Sharma		

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

<http://www.ligo.caltech.edu/>

1 Introduction

Gravitational waves (GWs) are distortions in the fabric of space-time, first predicted by Albert Einstein in 1915 as a result of general relativity. These waves propagate from energetic physical processes (colliding black holes, supernovae, colliding neutron stars) at the speed of light, carrying information about the events that created them. GWs are difficult to measure due to the minimal spatial distortion (strain) that they impose on Earth’s surface, on the order of 10^{-21} . The Laser Interferometer Gravitational-Wave Observatory (LIGO) was the first experiment to observe a GW in 2015 [1].

To reach a strain sensitivity capable of observing gravitational waves, LIGO must overcome many sources of noise including but not limited to: seismic noise, optical vacuum fluctuations, cosmic rays, and thermal noise [2]. This project will focus on simulating how mirror thermal fluctuations affect observed optical signals, in order to reproduce experimental data.

While previous studies have been done on the theoretical modeling of mirror thermal fluctuations [3, 4], there is still a mismatch between simulation predictions and experimental measurements. This is believed to originate from the nonstationary evolution of thermal distortions in the optics, due to incomplete knowledge of their initial thermal state and incomplete modeling of their thermal dynamics, which can introduce time-dependent systematic errors into the calibration and optical modes [6].

This project aims to construct accurate models of the interferometer that capture these thermal effects, and also utilize MCMC algorithms to analyze parameter sensitivity within the interferometer. The predictions of this project’s optical model can be validated against real LIGO data, specifically from stretches of data where the interferometer remains locked and the mirrors are allowed to reach a thermal steady-state. Data satisfying these criteria are not trivial to obtain, as whenever significant transient noise is introduced into the system, the laser will not be locked. Ultimately, these optical simulations will improve our understanding of thermal effects in LIGO and may enable the development of more robust active thermal compensation techniques, mitigating the impact of thermal noise and allowing for even higher strain sensitivity needed for future gravitational wave detectors.

2 Background

The project objectives addressed in this report are to combine the generalized FINESSE MCMC framework with the accurate LIGO thermal model constructed by the Richardson group. While working on this report, I mainly worked with ”synthetic data” which refers to a dataset of LIGO detector values generated from a FINESSE model with some Gaussian noise added to each detector reading. However, I also began work on utilizing real LIGO detector readings in the MCMC pipeline. All MCMC sampling was done with the framework outlined in the previous interim report.

Segment (GPS Time)	Interferometer Channel Name		
	L1:LSC-POP_A_LF_OUTPUT	L1:IMC-IM4_TRANS_SUM_OUT_DQ	L1:LSC-POP_A_RF9_Q_NORM_MON
[1422129869 - 1422217122)	2509.52 ct	56.66 ct	-41.17 ct ...
[1422475262 - 1422635418)	2511.95 ct	56.69 ct	-41.88 ct ...
[1422906429 - 1423042671)	2509.22 ct	56.62 ct	-39.29 ct ...
[1423116358 - 1423230279)	2505.82 ct	56.62 ct	-42.36 ct ...
[1424894576 - 1425055011)	2474.96 ct	56.45 ct	-38.55 ct ...
[1425352967 - 1425459306)	2478.77 ct	56.44 ct	-44.21 ct ...
[1425804561 - 1425894132)	2488.43 ct	56.38 ct	-36.32 ct ...
[1434602740 - 1434726018)	2211.49 ct	56.52 ct	-10.40 ct ...
[1435625437 - 1435775225)	2207.02 ct	56.46 ct	-4.64 ct ...
[1436216024 - 1436374703)	2205.43 ct	56.47 ct	-4.64 ct ...
[1438638690 - 1438728907)	2209.58 ct	56.43 ct	-6.01 ct ...
[1439676408 - 1439782598)	2208.66 ct	56.52 ct	-6.95 ct ...
[1441680250 - 1441767009)	2210.70 ct	56.46 ct	-7.18 ct ...
[1441893597 - 1441985474)	2212.81 ct	56.53 ct	-6.93 ct ...
[1444918046 - 1445009483)	2207.75 ct	56.60 ct	-11.30 ct ...

Table 1: ADC counts of selected LLO channels. Segments taken from periods where interferometer was locked for periods exceeding 24 hours.

The Richardson group has compiled data from the LIGO Livingston Observatory (LLO) during periods where it was known to be in a thermal steady-state (Table 1). Additionally, the group has constructed a mapping of the real channels with corresponding detectors in the FINESSE model. To interpret the results of the model with the values from the channel, however, we must consider the calibration factor that is used to convert the channel's ADC counts into units of power. The channels where this calibration factor has been measured and recorded are the detectors that we can primarily use in the MCMC method and in general model analysis. This results in the following list:

Detector	Finesse	IFO	IFO Channel	Calibration
Pin	44.7	44.7	L1:IMC-IM4_TRANS_SUM_OUTPUT	1
Parm	2.32e+05	2.41e+05	(1/2)*Pin*PRG*ArmGain	0.92
Pas_c	0.628	0.563	L1:ASC-AS_C_SUM_OUTPUT	0.000125
a_c0_refl_PRM	1.86	2.33	L1:LSC-REFL_A_LF_OUTPUT	0.00025
Pprc	1.86e+03	2.31e+03	L1:LSC-POP_A_LF_OUTPUT	0.92
PRG	40.7	40.7	L1:LSC-PRC_GAIN_MON	0.92
PRG9	122	49.1	L1:LSC-POPAIR_B_RF18_I_MON	0.019
PRG45	24.1	17.7	L1:LSC-POPAIR_B_RF90_I_MON	0.027
a_c0_dcpd	41	41	L1:OMC-DCPD_SUM_OUTPUT	0.82

Figure 1: Comparison table of FINESSE detector values (Finesse column) with experimental interferometer detector values after calibration (IFO column)

3 Approach/Method

3.1 Calibrated Channels

The inclusion of the calibrated channels greatly affects both the generalized MCMC pipeline and the thermal model.

3.1.1 MCMC

Assuming that we only consider these eight channels for the near future of this project, we lose information about the interferometer state compared to the base FINESSE model. This is because the base model has on the order of 50-100 detectors, including very informative field detectors. This immediately affected the quality of the corner plots produced from synthetic LIGO data:

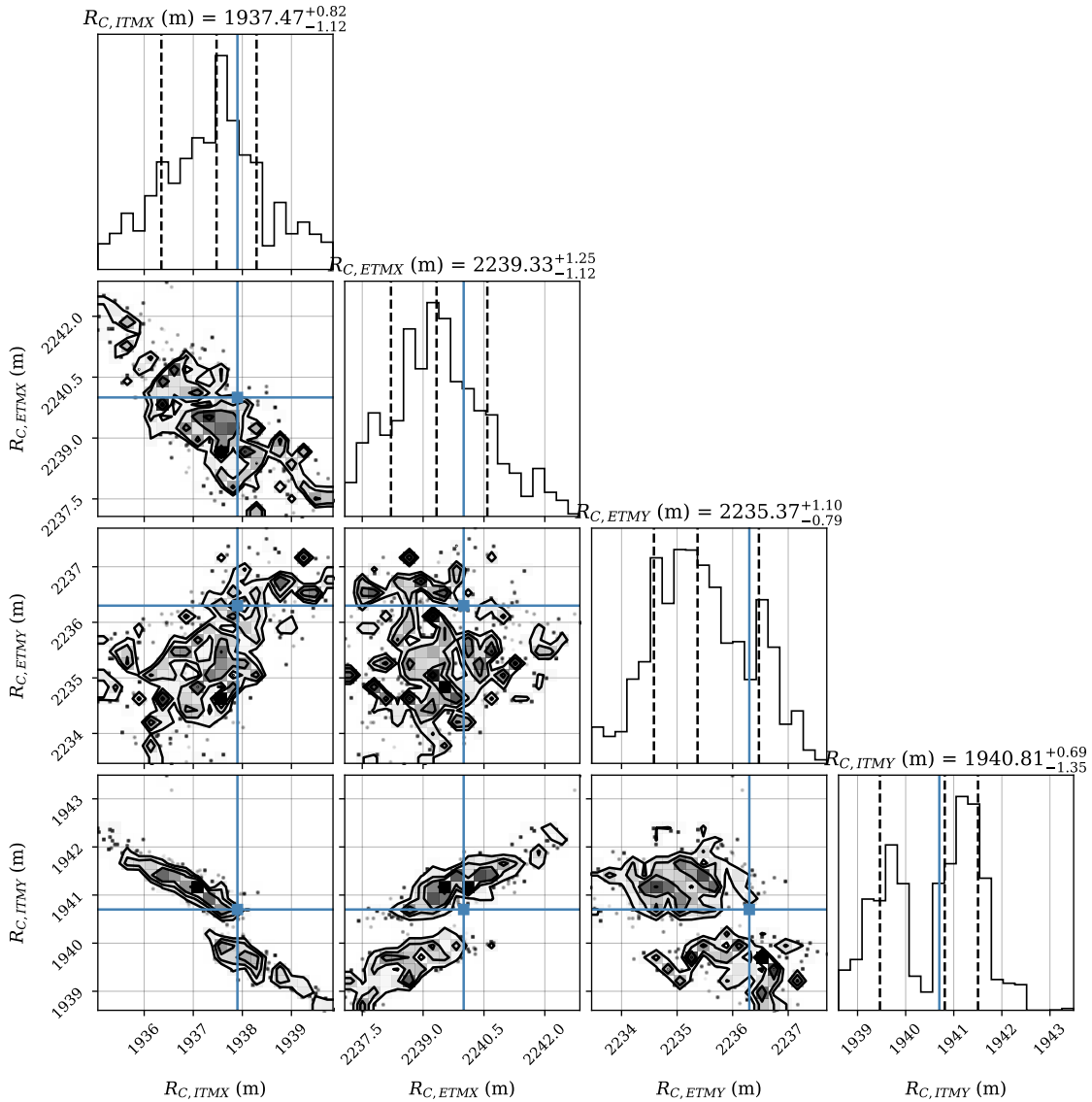


Figure 2: Corner plot of four test mass RoCs, using the eight FINESSE detectors from Figure 1 as MCMC objective. Blue lines indicate nominal RoC measurements

From these plots we can conclude that restricting our MCMC objective detectors can degrade the performance of the sampler. However, we can systematically estimate which detectors are most informative about which parameters by analyzing the change in posterior distribution based on the combination of detectors considered. These results may also be estimated a priori with a Fisher information analysis study [7].

Additionally, I produced corner plots using the experimental data as the MCMC objective. The synthetic data used to produce the plots in Figure 2 were replaced with the channel data after calibration. In these studies I compared Gaussian priors versus uniform priors for the test mass' radius of curvature (RoC):

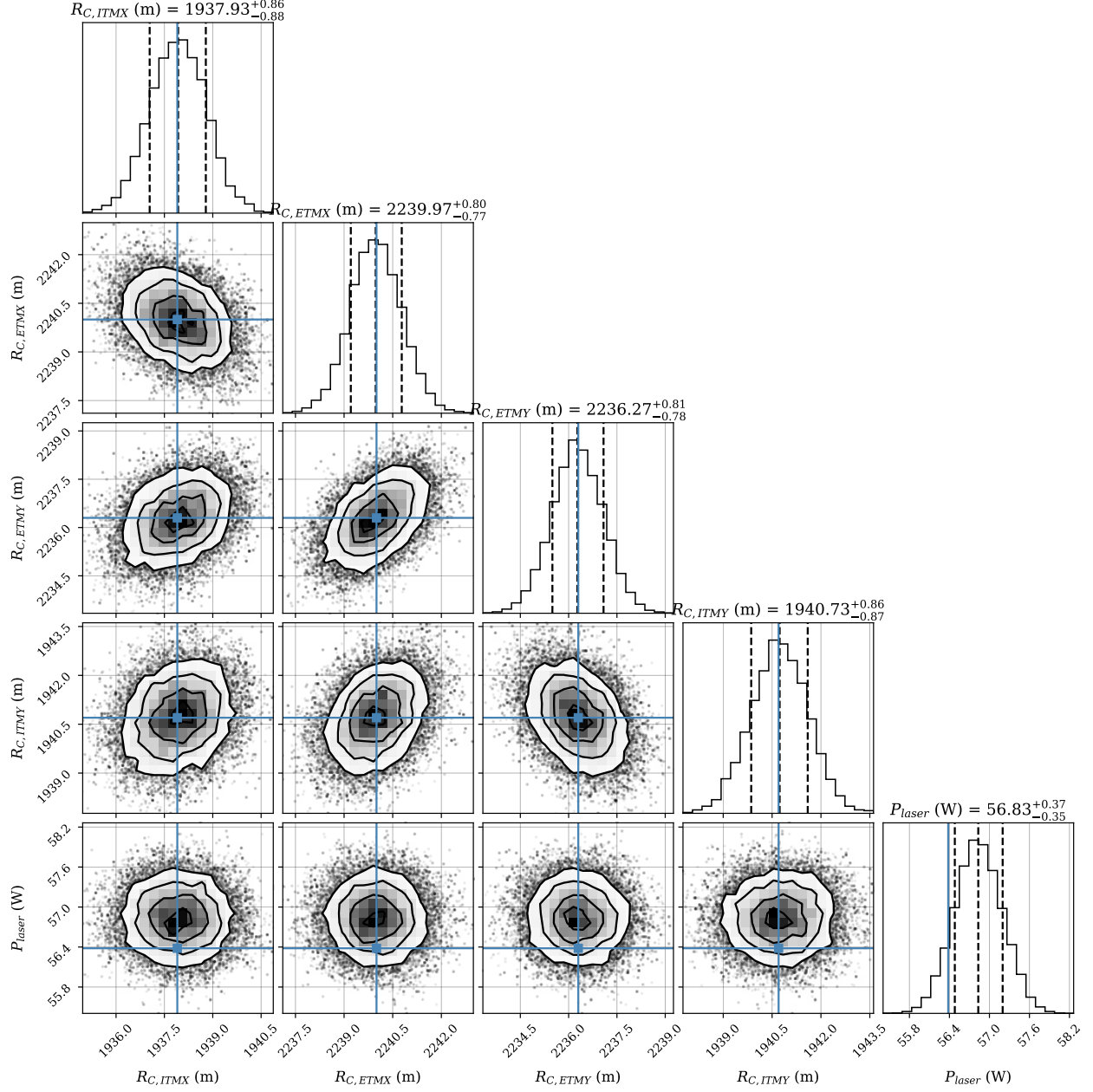


Figure 3: Corner plot produced with interferometer channel data as MCMC objective, using Gaussian prior for each test mass centered at nominal value with standard deviation of one meter.

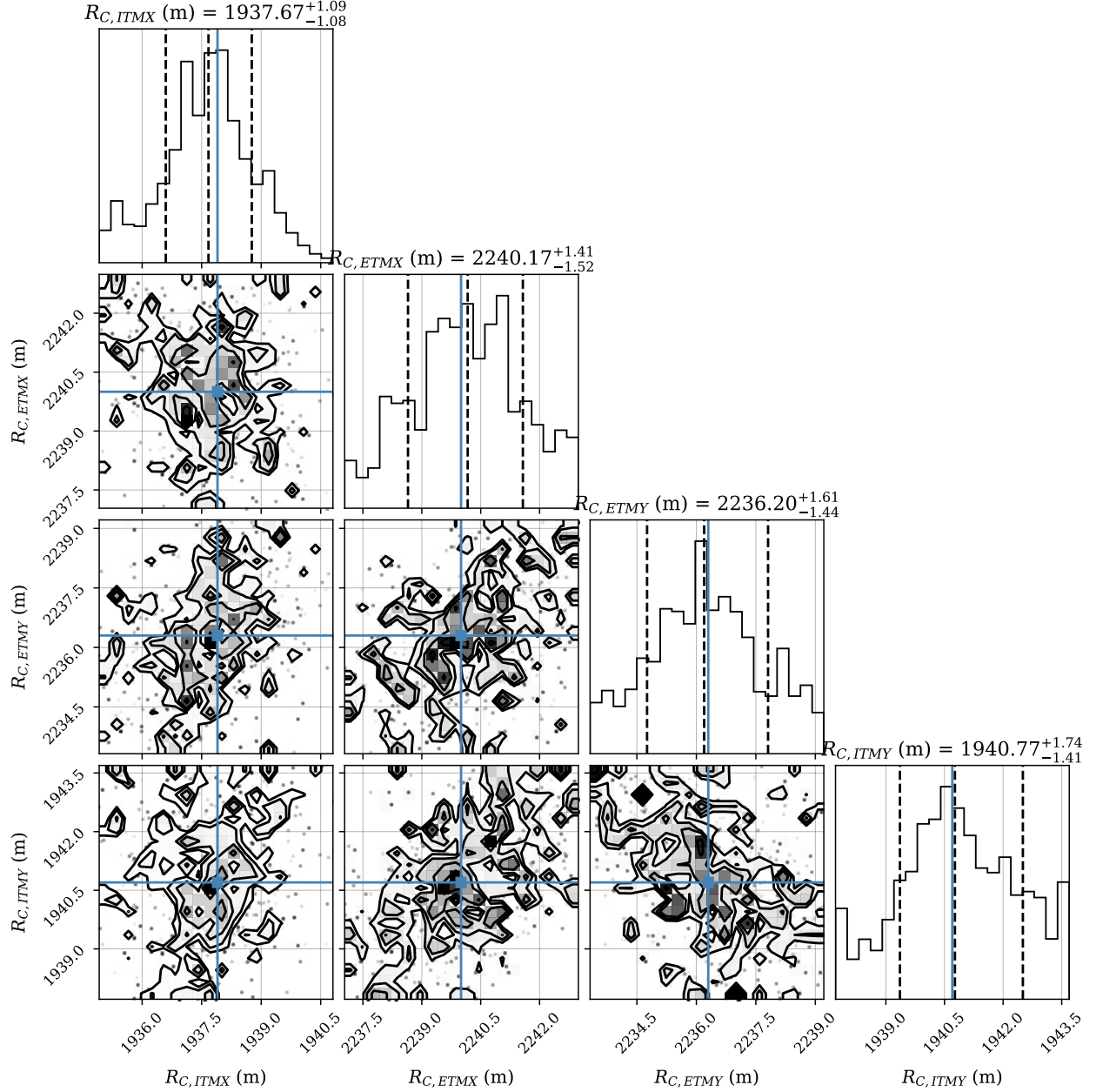


Figure 4: Corner plot produced with interferometer channel data as MCMC objective, using uniform prior for each test mass centered at nominal value plus or minus three meters.

We can see that the choice of priors is extremely important for the quality of the corner plot distributions. While some physical information is still carried by the uniform prior plot, as seen by the correlations between combinations of test mass RoCs, the distributions are much less interpretable compared to the distributions drawn with Gaussian priors.

Another consideration for the real detector data is that we need to split up the channels into input channels and output channels. For example, the channel corresponding to the input power of the laser is IMC-IM4_TRANS_SUM_OUTPUT and it has been used to set the input power of the FINESSE model. Similarly, the channel OMC-DCPD_SUM_OUTPUT is used to calibrate the DARM DC offset. This calibration step was recently incorporated into

the likelihood evaluations of the MCMC sampler. Channels like these can be considered design parameters and more thought must be put into how to meaningfully use them in the MCMC. For example, the choice of their values may be included in a prior distribution and then included as a free parameter in the sampler. This is discussed further in Section 4.

3.1.2 Thermal Effects

Including thermal effects into the sampler is important for multiple reasons. Not only would it produce more accurate detector values, increasing the sensitivity of the MCMC sampler, but it would also allow us to sample a new host of parameters such as ring heater power or test mass heating efficiency. For example, in Figure 1 the channels highlighted in green are those where the FINESSE model values match closely with the measured values. These detectors do not match closely when compared to the non-thermal ("cold") models. However, this comes at the cost of computational speed since the thermal models can take orders of magnitude more time to run than the cold FINESSE model. So while accurate thermal models have been constructed by the Richardson group, there also has been work done in simplifying the model and considering how to implement them in the MCMC pipeline while keeping runtime reasonable. The two approaches that have been weighed are finite element analysis (FEA) and analytic approaches for simulating test mass heating. The FEA approach is generally more accurate but can take much longer to run compared to the analytic approach which uses the result of the paper by Hello and Vinet to solve for test mass distortions due to laser heating [5]. Separately from developing the MCMC pipeline, I have been testing the different thermal models to determine what approach can best combine accuracy and speed before implementation into the sampler.

4 Future Work

First, we must choose the most suitable thermal model for the sampler and run it with a choice of design parameters and free parameters that closely match the real detector values. This could be considered a "pretuning" step. Then we can use this choice of parameters for the prior distribution to sample around. For example, if we see that a simulated Arm Loss parameter of 75 ppm is what produces the most accurate results, use a Gaussian distribution with mean 75 ppm and reasonable standard deviation. The sampler can then use this accurate thermal model as a starting point and begin varying the parameters to allow us to estimate parameter sensitivity as well as sample alternative interferometer operating points. If the sampler is accurate, the choice of initial conditions would not affect the final distributions, however, this would significantly reduce the burn in period.

References

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