LIGO-T890011-00-B

#63

List of 3/15/89

LIGO PROJECT ENGINEERING

CALIFORNIA INSTITUTE OF TECHNOLOGY

TO	File	**DATE**	Mar. 15, 1989
FROM	W. E. Althouse **EXTENSION** 4481	**MAIL CODE**	102-33

SUBJECT Evaluation of Baffle Requirements for LIGO beam tubes

The attached handwritten notes were prepared by Rai Weiss to evaluate the principles, properties and requirements for baffles in LIGO beam tubes, as discussed in Kip Thorne's document "Light Scattering and Proposed Baffle Configuration for the LIGO" (1/11/89) and Rai Weiss's companion document "Optical Properties of the LIGO Beam Tubes" (1/17/89, amended 2/19/89).

The notes are divided into two parts: the first part evaluates the general problem for several specific cases (14 pages), while the second part evaluates the special optical properties of corrugated tubes (6 pages); the results are tabulated on page 9 of the first section.

Rai has assumed (quite properly, I think) that the baffles are spaced uniformly in the tube. As Rai points out on page 8 of the first section, Kip proposed a non-uniform spacing optimization which results in fewer baffles installed in the beam tubes. This assumption will be reevaluated if baffle manufacturing or installation becomes a significant cost driver.

10-28 1989

TO BILL ALTHOUSE

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SUMMARY OF PRESENT ESTIMATES FOR TUBE MOTION AND BAFFLING WITH AND WITHOUT ADDITIONAL TUBE ROUGHENING BOTH FOR STRAIGHT TUBING AND CORRUGATED TUBING

REFERENCES: "LIGHT SCATTERING AND PROPOSED BAFFLE CONFIGURATION FOR THE LIGO",
K.S. THORNE SECOND DRAFT 1/11/1989

"OPTICAL PROPERTIES OF THE LIGO BEAM TUBES" R. WEISS 1/17/1989 AND
ERROR 21989 R. WEISS 2/19/89

ASSUMPTIONS MADE IN NUMERICAL ESTIMATES

L = LENGTH OF TUBE 4 Km = 4×10^5 cm
R = RADIUS OF TUBE 24" ⇒ 61 cm
λ = WAVELENGTH OF LIGHT $0.5 \rightarrow 1.0 \times 10^{-4}$ cm
η = QUANTUM EFFICIENCY OF PHOTODETECTOR = 0.9

NOISE

REFERENCE SEISMIC MOTION (ASSUMED ISOTROPIC)

$x(f) \sim 10^{-7}\ \mathrm{cm/Hz^{1/2}}$ $\quad 1 < f < 10$ Hz

$x(f) \sim 10^{-5}/f^2\ \mathrm{cm/Hz^{1/2}}$ $\quad f > 10$ Hz

REFERENCE SEISMIC FLUCTUATION IN ANGLE OF TUBE AXIS

$$\mu(f) \sim \frac{2\pi\, x(f)\, f}{c_T}\, T(f)$$

c_T = TRANSVERSE SOUND SPEED OF TUBE $\sim 3 \times 10^5$ cm/sec

c_{Tc} = TRANSVERSE SOUND SPEED OF CORRUGATED TUBE $\sim 3 \times 10^4$ cm/sec

$T(f)$ = TRANSFER FUNCTION OF TUBE MOTION/GROUND MOTION
~ 10 TO ACCOUNT FOR RESONANCES AT LOW FREQUENCIES (10 – 100 Hz STRAIGHT TUBES)
(1 – 10 Hz CORRUGATED TUBES)

$\mu(f)$ RADIANS/$\mathrm{Hz^{1/2}}$

	STRAIGHT	CORRUGATED
$1 < f < 10$ Hz	$2 \times 10^{-11} f$	$2 \times 10^{-10} f$
$f > 10$ Hz	$2 \times 10^{-9}/f$	$2 \times 10^{-8}/f$

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REFERENCE SENSITIVITY

QUANTUM LIMITED ANTENNA OPTIMIZED FOR FREQUENCY f

$m = 10^6$ gm $\qquad T_{STORE}$ = STORAGE TIME OF LIGHT = $\frac{1}{2\pi f}$

$$h_{QL}(f) = \left(\frac{8\hbar}{m}\right)^{1/2} \frac{1}{2\pi f L} \approx \frac{4\times 10^{-23}}{f} \quad \text{STRAIN}/\text{Hz}^{1/2}$$

GOAL: KIP AND I HAVE SET A GOAL THAT SCATTERING NOISE SHOULD BE KEPT, IN THESE PRELIMINARY ESTIMATES, TO A LEVEL

$$\underset{\underline{\text{GOAL}}}{h_{SCAT}(f)} \leq \frac{1}{10}\, h_{QL}(f)$$

FUNDAMENTAL SCATTERING AND RECOMBINATION SOURCE

MIRROR SCATTERING FUNCTION

$$\frac{dP_{sc}(\theta)}{P\, d\Omega} = \frac{10^{-6}}{\theta^2} = \frac{\alpha}{\theta^2}$$

CAVEATS

1) EXTRAPOLATION IS BEING MADE TO $\theta \sim 10^{-4}$; BEST PRESENT MEASUREMENTS $\theta \geq 10^{-2}$ WITH POORER MIRRORS FOR WHICH $\alpha \sim 3\times 10^{-5}$. [SUPERMIRRORS, $\alpha \sim 10^{-6}$]

2) EXPECTATION IS THAT FUNCTIONAL DEPENDENCE WILL NOT BE STRONGER THAN $1/\theta^2$ AT SMALLER ANGLES AND MAY FLATTEN.

3) CLEARLY AN AREA WHERE PROJECT WILL HAVE TO EXPEND EFFORT -

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SUMMARY ASSUMES

1) BAFFLING EXTENDS ALONG FULL 4 Km TUBE

I AM ASSUME THAT THERE IS NO SPECIAL ADVANTAGE TO PLACE BAFFLES IN ONLY ½ OF THE TUBE LENGTH ONCE THE DECISION IS TAKEN TO EMPLOY BAFFLES. (KIP CARRIES BOTH ½ AND FULL BAFFLING OPTIONS IN HIS DOCUMENT)

2) RETAIN THE OPTION TO MEET THE DESIGN GOAL WITHOUT OUTPUT MODE FILTERS.

THE SUMMARY GIVES BAFFLING AND TUBE PROPERTIES FOR INTERFEROMETERS WITH AND WITHOUT OUTPUT MODE FILTERS. CONSIDERING THAT WE HAVE NOT USED OUTPUT MODE FILTERS IN THE PROTOTYPES UP TO NOW, IT IS PRUDENT CONSIDER THIS OPTION FOR THE LIGO AS WELL, EVEN THOUGH IT MAKES MORE STRINGENT DEMANDS ON THE REDUCTION OF SCATTERED LIGHT.

3) THERE WILL BE MORE BAFFLES THAN PUMP STATIONS ALONG THE 4 Km LENGTH

THE ELEGANT IDEA OF MAKING THE BAFFLES INTEGRAL WITH THE PUMP STATIONS AND THEREBY CHANGEABLE IS NOT VIABLE. THE RESULTS OF THE PRELIMINARY ANALYSIS INDICATE THAT BOTH TUBE AND BAFFLE MOTIONS CAUSE SCATTERING NOISE; SO PUTTING ONLY BAFFLES AT FIRM SUPPORTS IS NOT ADEQUATE. THE CONCEPT NOW ENVISAGED IS A SHEET METAL STRUCTURE PLACED IN THE TUBES; THE DESIGN TRADE OFFS ARE BETWEEN

a) SMOOTH VS ABSORBING BAFFLES TO REDUCE BACKSCATTERING

b) THE NUMBER OF BAFFLES VS THE ATTENUATION BY THE TUBES THEMSELVES

c) THE NUMBER OF BAFFLES VS CLEAR APERATURE

d) SCATTERING BY BAFFLE EDGES VS NUMBER OF BAFFLES

4) COHERENCE IN THE SCATTERED FIELD AT THE OUTPUT OF THE INTERFEROMETER CAN BE NEGLECTED

5) THE BASELINE BAFFLING STRATEGY IS TO CONVERT GLANCING RAYS TO LARGER ANGLES AND TO THEN USE THE ABSORPTION BY THE TUBES ON MULTIPLE ENCOUNTERS TO ATTENUATE AND ISOTROPIZE THE SCATTERED LIGHT. THIS CONCEPT EXPLOITS THE UNIQUE PROPERTY FOR THE LIGO, THE LARGE RATIO OF L/R.

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BACKSCATTERING BY THE BAFFLES

K.S.T PAGE 23 EQ 3.29 NO MOOR FILTER
EQ 3.30 WITH MOOR FILTER

NO MOOR FILTER

$$h(f) = 2\alpha^{1/2}(1-\eta)\left(\frac{2\pi f L}{c}\right)\left(\frac{d\sigma}{dA\,d\Omega}\right)^{1/2}\left(\frac{\lambda}{L}\right)^{1/4}\left(\frac{(\lambda L)^{1/2}}{Y_0}\right)\left(\frac{R}{\ell_1}\right)^{1/2}\frac{X(f)}{L}$$

Y_0 = CLOSEST DISTANCE OF BEAM CENTER TO A BAFFLE EDGE

ℓ_1 = DISTANCE FROM MIRROR TO FIRST BAFFLE

$$\frac{d\sigma}{dA\,d\Omega} = \frac{dP_s(\theta_{sc})}{d\Omega\,P} = \underbrace{G\left(\frac{\pi}{4}, \frac{3\pi}{4}, 0\right)}_{\longrightarrow \text{RW PAGE 7 EQ 1, EQ 2}}$$

WITH MOOR FILTER

$$h(f) = 2\sqrt{2}\,\alpha\left(\frac{2\pi f L}{c}\right)\left(\frac{d\sigma}{dA\,d\Omega}\right)^{1/2}\left(\frac{\lambda}{L}\right)^{1/2}\left(\frac{(\lambda L)^{1/2}}{Y_0}\right)^{3/2}\left(\frac{H}{\sqrt{\lambda L}}\right)^{1/2} N_b^{1/2}\,\frac{X(f)}{L}$$

N_b = TOTAL NUMBER OF BAFFLES

H = HEIGHT OF BAFFLES

CONDITIONS ON BAFFLE SURFACE —

ASSUME STANDARD SHEET METAL **NOT** OPTICALLY POLISHED

ASSUME GAUSSIAN SURFACE: σ = rms SURFACE ROUGHNESS
T = CORRELATION LENGTH OF ROUGHNESS

$$G(\pi/4, 3\pi/4, 0) = \frac{1}{16\pi}\left(\frac{T}{\sigma}\right)^2 e^{-\left(\frac{T}{2\sigma}\right)^2} \qquad \left(\frac{2\pi\sigma}{\lambda}\right) >> 1$$

ROUGH SURFACE

SAMPLE NUMBERS

TYPICAL SHEET METAL SURFACE ALUMINIUM OR 304 STAINLESS

$\sigma \sim 100$ MICROINCH ROUGHNESS $\quad \frac{2\pi\sigma}{\lambda} \sim 32 \quad \lambda = \frac{1}{2}\mu$

IF $T/\sigma \sim 1$

$$G(\pi/4, 3\pi/4, 0) \cong 1.5 \times 10^{-2}$$

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SAMPLE NUMBERS FOR BACKSCATTERING NOISE WITH THIS SHEET METAL SURFACE

NO MODE FILTER

USE: $\lambda = 0.5$ $\quad Y_0 = 20$ cm

$$h(f) = \frac{3 \times 10^{-22}}{f \cdot \ell_1^{1/2}} \quad \text{strain}/\text{Hz}^{1/2}$$

THE FIRST BAFFLE DISTANCE $\ell_1 \geq 10^4$ cm

SO THAT $h(f) \leq \frac{1}{10} h_{gL}(f)$

WITH MODE FILTER

$$h(f) = \frac{5 \times 10^{-28}}{f} N_b^{1/2}$$

USE $H = 6$ cm

TO STAY LESS THAN $1/10 \; h_{gL}(f)$

ALLOWED TO USE $N_b < 6 \times 10^7$ BAFFLES

CONCLUSIONS ON BACKSCATTERING BY BAFFLES

1) NO SPECIAL CARE IS REQUIRED IN THE SURFACE QUALITY OF THE BAFFLE TO REDUCE BACKSCATTERING

2) IF THE FIRST BAFFLE IS PLACED CLOSER TO THE MIRROR THAN 100 METERS, THE SURFACE OF THE BAFFLE SHOULD BE MADE LESS SCATTERING BY POLISH OR BLACKENING.

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SCATTER PROPAGATION ALONG THE TUBES

THE FUNDAMENTAL RELATION FOR INCOHERENT SCATTERING NOISE IS KST P 13 EQ 3.7

$$h_{scat}(f) = \frac{\lambda f}{c}\left[\int_{\Omega} P_{REC}(\theta)\left(\frac{dP_{sc}/dA\,d\Omega\,df}{P_{IN}/\lambda L}\right)d\Omega\right]^{1/2}$$

WHERE $P_{REC}(\theta)$ IS THE RECOMBINATION PROBABILITY OF SCATTERED LIGHT WITH THE MAIN BEAM

WITH OUTPUT MODE FILTER

$$P_{REC}(\theta) = \frac{2\alpha}{\theta^2}\,\frac{\lambda}{L}$$ KST P12 EQ 3.5

WITHOUT OUTPUT MODE FILTER

$$P_{REC}(\theta) = \frac{(1-\eta)^2}{2\theta}\left[\frac{\lambda}{L}\right]^{1/2}$$ KST P12 EQ 3.6

THE DOMINANT NOISE TERM WITH BAFFLING IS DUE TO SEISMICALLY INDUCED SLOPE FLUCTUATIONS OF THE TUBES. THE MAJOR PROCESS IS DIFFRACTION AT A BAFFLE TOWARD THE TUBE WALL FOLLOWED BY MULTIPLE REFLECTION TRANSPORT BETWEEN THE BAFFLES - "DIFFRACTION - AIDED REFLECTION".

THE NOISE TERM FOR THIS PROCESS IS

$$\frac{dP_{sc}}{dA\,df} = \underset{\text{UNMODULATED BY MOTION}}{\left.\frac{dP_{sc}}{dA}\right|}\left[\pi\frac{(2L-\ell_n)}{\lambda}\,\theta_0\,\mu(f)\right]^2$$ KST P17 EQ 3.18

WHERE

$\frac{dP_{sc}}{dA}$ IS THE UNMODULATED SCATTERED INTENSITY AT THE OUTPUT

ℓ_n IS THE DISTANCE BETWEEN THE SCATTERING POINT AND THE OUTPUT MIRROR

$\mu^2(f)$ IS THE POWER SPECTRUM OF SEISMICALLY DRIVEN SLOPE FLUCTUATIONS OF THE TUBE

θ_0 IS THE MINIMUM GRAZING ANGLE FOR

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WHICH THE ATTENUATION OF MULTIPLE REFLECTION PROPAGATION EXCEEDS $10^8 \to 10^9$

THE ATTENUATION IS GIVEN BY

$$[\langle R(\theta)\rangle]^{L\theta/2R} = \text{ATTENUATION}$$

RW P3, P10

WHERE $\langle R(\theta)\rangle$ IS THE AVERAGE POWER REFLECTIVITY WHICH IS LESS THAN UNITY DUE BOTH TO ABSORPTION AND ANGULAR REDISTRIBUTION OF THE INCIDENT BEAM AT THE WALL

θ_0 ESTABLISHES BAFFLE NUMBER, HEIGHT, AND SPACING AND IS DEPENDENT ON TUBE DESIGN AND ROUGHNESS.

ASSUMING UNIFORM BAFFLE SPACING ALONG THE TUBE, THE SEPARATION OF BAFFLES IS

$$S = \frac{2(H - \delta H)}{\theta_0}$$

KST P19
EQ 3.24A

WHERE H IS THE HEIGHT OF THE BAFFLE AND δH IS THE HEIGHT SAFETY FACTOR TO ALLOW FOR ATTENUATION OF DIFFRACTION AIDED REFLECTION. KIP CHOSE H = 6 cm AND δH = 1 cm. (RW AGREES THIS A GOOD INITIAL CHOICE)

NOTE: THE NON UNIFORM SPACING OF BAFFLES SUGGESTED BY KIP WAS MOTIVATED BY REDUCING THE BAFFLE NUMBER, IN PART BECAUSE HE EXPECTED THE BAFFLES TO BE EXPENSIVE. I SEE NO STRONG ARGUMENT NOW FOR REDUCING THE NUMBER OF BAFFLES AND SEE AN OPERATIONAL ADVANTAGE DURING CONSTRUCTION TO KEEP THE BAFFLE SPACING UNIFORM. THE ONLY SCIENTIFIC ARGUMENT FOR REDUCING BAFFLE NUMBER COMES FROM THE BACK SCATTERING NOISE BUT THIS HAS A LARGE MARGIN OF SAFETY (SEE PAGE 6)

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ESTIMATES OF θ_0
WITH ATTENUATION OF 80 db IN 4 km
$\lambda = 0.5\,\mu$ $H = 6$ cm $\delta H = 1$ cm $\Rightarrow$ 2 db IN 100 METERS

TUBE DESIGN	σ/λ	σ (cm)	g/θ^2	T/σ	θ_0 (rad)	N_b	REFERENCE
SMOOTH STAINLESS	0	0	0	∞	0.1	4×10^3	RW P3
STANDARD STAINLESS 100 μ INCH SURFACE	5.1	2.5×10^{-4}	4.1×10^3	1	6×10^{-2}	2×10^3	RW P7 F
ROUGHENED STAINLESS 1000 μ INCH BUMPS	51	2.5×10^{-3}	4.1×10^5	1	6.1×10^{-3}	2.4×10^2	RW P7 F
ROUGHENED STAINLESS 10 000 μ INCH BUMPS	510	2.5×10^{-2}	4.1×10^7	1	6.1×10^{-3}	2.4×10^3	RW P7 F
ROUGHENED STAINLESS 1000 μ INCH BUMPS	51	2.5×10^{-3}	4.1×10^5	3	2.4×10^{-2}	9.8×10^2	RW P7
SMOOTH CORRUGATED STAINLESS $Y_0 = 1.27$ cm $\lambda = 12.7$ cm	0	0	0	∞	2.3×10^{-3}	9.1×10^1	RW C 3,
BUMPY CORRUGATED $\sigma_{Y_0} = 1\%\ R = .6$ cm MANUFACTURING TOLERANCE	1.2×10^4	0.6	2.3×10^{10}	∞	2.3×10^{-3}	9.1×10^1	RW C
ROUGHENED CORRUGATED 1000 μ INCH BUMPS	51	2.5×10^{-3}	4.1×10^5	1	2.3×10^{-3}	9.1×10^1	RW 4T 3/18

↑
per 4 km

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DISCUSSION OF TABLE

ONLY DIFFUSE SCATTERING IS CONSIDERED AS AN ATTENUATION MECHANISM. IT IS FOR THIS REASON THAT INCREASED ROUGHENING DOES NOT HELP. IF WE ARE ULTIMATELY DOMINATED BY COHERENT SCATTERING INCREASED ROUGHENING INCREASES g (RW PAGE 8) WHICH HELPS ENORMOUSLY.

TAKING KIP'S ESTIMATE THAT COHERENT SCATTERING IS UNIMPORTANT, THE BIG ADVANTAGE IN ROUGHENING OCCURS BETWEEN 100 μ INCH → 1000 μ INCH SURFACES FOR STRAIGHT TUBING

THE CORRELATION LENGTH, T, IS MORE IMPORTANT THAN σ ONCE $g >> 1$.

FOR CORRUGATED TUBES THE PRELIMINARY ESTIMATE FOR THE ATTENUATION IS SO LARGE THAT ROUGHENING DOES NOT ADD TO THE ATTENUATION ALREADY PROVIDED BY THE ANGULAR REDISTRIBUTION OF THE BEAM

THE ROUGHENING AND IRREGULARITIES IN THE CORRUGATED TUBE WOULD INCREASE THE ATTENUATION OF COHERENT SCATTERING WERE IMPORTANT

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NOISE DUE TO DIFFRACTION AIDED REFLECTION

NO OUTPUT MODE FILTER

KST P21 EQ 3.25b

$$h_{SCAT}(f) = \frac{1}{\sqrt{3}}\,\frac{1}{16\pi^2}\,\frac{\lambda}{\delta H}\,\alpha^{1/2}(1-\eta)\,\frac{2\pi f L}{c}\left[\frac{(\lambda L)^{1/2}}{R}\right]^{3/2}\left[\ln\left(\frac{L\theta_0}{4R}\right)\right]^{1/2}\mu(f)$$

USING $\theta_0 \sim 6 \times 10^{-3}$ RADIANS [VERY INSENSITIVE TO θ_0]

$h(f)$ STRAIGHT TUBE $= 1.4 \times 10^{-25}$ STRAIN/$\mathrm{Hz}^{1/2}$ $f > 10$ Hz

CROSSES $\frac{1}{10}\, h(f)_{GL}$ AT ABOUT 30 Hz

$h(f)$ CORRUGATED TUBE $= 1.4 \times 10^{-24}$ STRAIN/$\mathrm{Hz}^{1/2}$ $f > 10$ Hz

CROSSES $\frac{1}{10}\, h(f)_{GL}$ AT ABOUT 3 Hz

WITH OUTPUT MODE FILTER

KST P22 EQ 3.27b

$$h_{SCAT}(f) = \frac{1}{\sqrt{3}}\,\frac{1}{64\pi^2}\,\frac{\lambda}{\delta H}\,\alpha\,\frac{2\pi f L}{c}\left[\frac{(\lambda L)^{1/2}}{R}\right]^{2}\mu(f)$$

$h(f)$ STRAIGHT TUBING $\cong 4 \times 10^{-29}$ STRAIN/$\mathrm{Hz}^{1/2}$

$h(f)$ CORRUGATED TUBING $\cong 4 \times 10^{-28}$ STRAIN/$\mathrm{Hz}^{1/2}$

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OTHER CONSIDERATIONS

1) TUBE ALIGNMENT AND OUT OF ROUNDNESS
PRIMARY CONCERN IS THE EFFECT OF COHERENT SCATTERING FOR BEAMS ON THE TUBE AXIS AND SECOND ORDER TERMS IN THE DIFFUSE SCATTERING DUE TO SLOPE FLUCTUATIONS OF THE TUBE

IN SEC III KST THE RECOMMENDATION IS MADE TO PUT LINEAR OFFSETS OF THE TUBES OF ~ 1 cm IN THE VARIATION AROUND THE AVERAGE LINE OF SITE DOWN THE TUBES

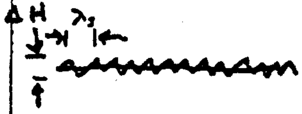
THE RECOMMENDATION SHOULD BE ADOPTED IT RAISES THE BAFFLE HEIGHT FROM 6 TO 7 cm KEEPING THE δH OF 1 cm, IN FURTHER TRADE OFF STUDIES ONE COULD RECOVER THE APERATURE BY PUTTING APPROXIMATELY 15% MORE BAFFLES IN.

AN OUT OF ROUNDNESS OF $\frac{r_a - r_b}{\langle r \rangle} \sim 1/100$

IS ALSO RECOMMENDED TO REDUCE THE POSSIBILITY OF COHERENT SCATTERING

2) MY PRESENT CONCEPT OF THE BAFFLES IS A SHEET METAL TRIANGLE PLACED AS A HELIX IN THE BEAM TUBES, THE SURFACE FINISH BACK TOWARD THE MIRRORS CAN BE AS ROUGH AS 100 μ INCHES THE ANGLE OF THE BAFFLE SIDES IS NOT CRITICAL I BELIEVE IT CAN BE $\theta = 45 \pm 5°$ (THIS NEEDS FURTHER EVALUATION)

THE BAFFLE EDGE COULD BE ROUGHENED TO REDUCE COHERENT SCATTERING. IF IT IS ROUGHENED THE VARIATION IN HEIGHT



$$\Delta H \geq \frac{\lambda L}{2R} \sim 3.5 \text{ mm AT } 1.06\mu$$

AND $\lambda_s < \Delta H$

THE ROUGHENING CAN BE PERIODIC OR RANDOM IT WILL GET SCRAMBLED BY THE MULTIPLE BAFFLES.

UNCERTAINTIES AND FUTURE WORK

1) I BELIEVE THERE IS ENOUGH INFORMATION TO MAKE A FIRST CUT COSTING AND CONCEPTUAL DESIGN OF THE BAFFLING.

2) IT IS EXTREMELY UNLIKELY THAT WE WILL IMPROVE THE BAFFLING DESIGN OR GET MIRRORS WITH SMALL ENOUGH α SO THAT A COVER FOR THE TUBES BECOMES UNNECESSARY. IF WE DO NOT INTEND TO COMPROMISE THE LIGO AT THE QUANTUM LIMIT AND WISH TO RETAIN THE OPTION OF NOT USING OUTPUT MODE FILTERS A COVER IS NEEDED.

NEITHER KIP NOR I ARE SUFFICIENTLY CONFIDENT OF THE ESTIMATES THAT WE WOULD BANK ON A FACTO OF 10 IN THE NOISE ESTIMATE OF $h(f)_{scat}$

3) A CONTINUING UNCERTAINTY IN THE ESTIMATES IS

1) HAVE ALL MECHANISMS BEEN LOOKED AT?

2) IS COHERENCE REALLY UNIMPORTANT ?

3) THE SCATTERING BY INTERFEROMETER COMPONENTS, MIRROR EDGES, WIRES, MAGNETIC CONTROLLERS ETC. ?

ONCE THE HEAT OF THE PRESENT PROPOSAL AND CONCEPTUAL DESIGN ACTIVITIES HAS ATTENUATED, KIP AND I RECOMMEND THAT A COMPUTER MODEL OF THE BAFFLING STRATEGY WITH AN INSTALLED INTERFEROMETER BE CARRIED OUT.

4) DIRECT MEASUREMENTS THAT WOULD HELP FUTURE ESTIMATES

1) PHOTODETECTOR UNIFORMITY

2) MEASUREMENT $\dfrac{dP_{scat}(\theta)}{P\, d\Omega}$ FOR LIGO TYPE MIRRORS AT $\theta < 1 \times 10^{-2}$ RADIANS

3) DIRECT DIFFUSE SCATTERING MEASUREMENTS AT GRAZING INCIDENCE OF CANDIDATE BAFFLE AND TUBE MATERIAL.

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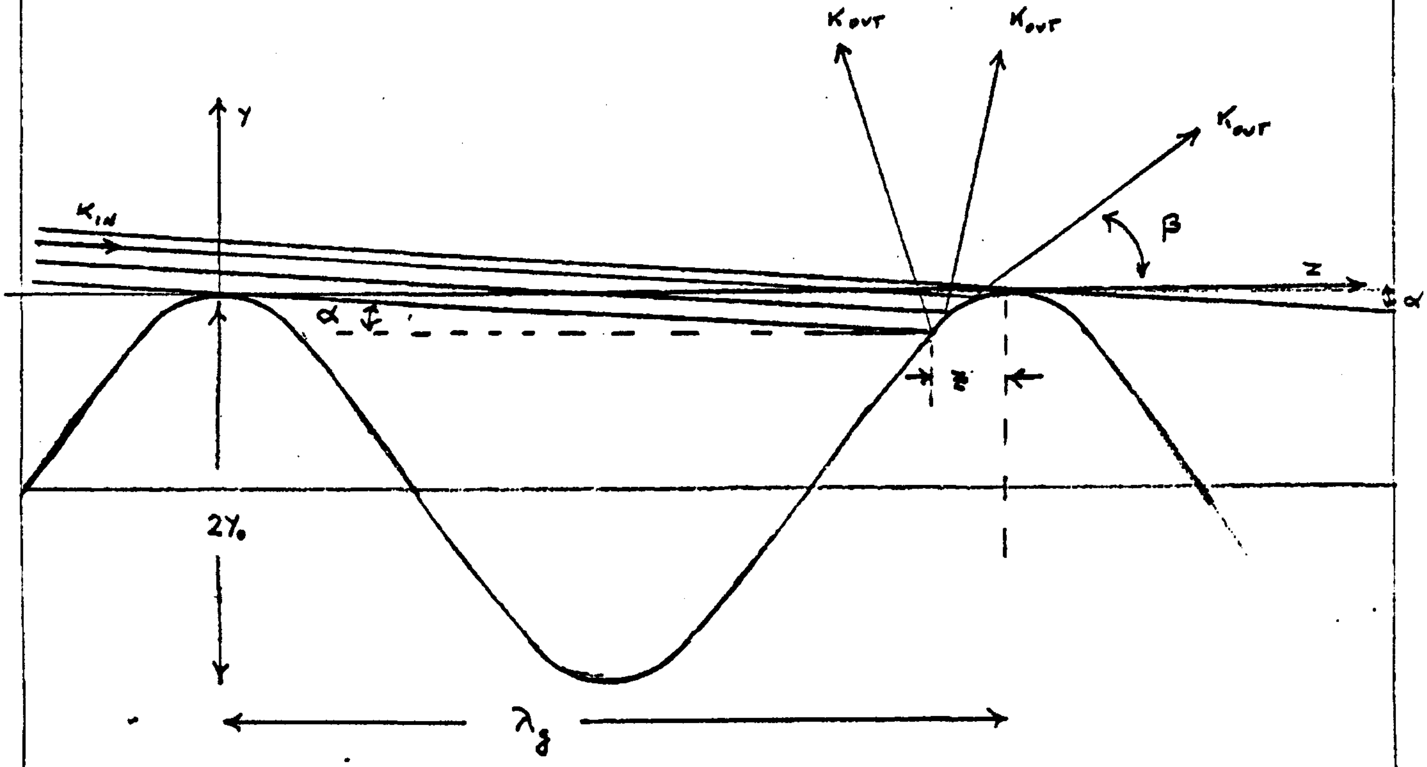
ANALYSIS OF CORRUGATED TUBE AS LIGHT SCATTERER

OUTLINE:
1) DETERMINE RAY TRAJECTORIES AND INTERSECTIONS WITH CORRUGATED SURFACE
2) DETERMINE DISTRIBUTION OF REFLECTIONS FOR SINGLE INPUT ANGLE
3) DETERMINE BEAM DILUTION BY THE REFLECTION



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ASSUME PLANE WAVE INCIDENT, LOOK AT INDIVIDUAL RAYS

EQUATION OF CORRUGATED SURFACE

$$Y(z) = Y_0 \left[\cos\left(\frac{2\pi z}{\lambda_g}\right) - 1 \right]$$

TYPICAL VALUES FROM LARRY JONES

$Y_0 = 1.27$ cm

$\lambda_g = 12.7$ cm

ASSUME $\underline{\alpha} < .2$ GLANCING ANGLES

EQUATION OF RAYS

$$Y(z) = Y(0) - \alpha z$$

LIMITING RAYS THAT HIT NEXT CONVOLUTION AFTER $z=0$

$Y(\lambda - z) = -\alpha(\lambda_g - z)$ GRAZING AT $z=0$

$Y(0) = \alpha \lambda_g$ GRAZING AT $z=\lambda$

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INTERSECTION OF LIMITING RAYS WITH SURFACE

ASSUME $Z/\lambda_g \ll 1$

FOR SURFACE

$$Y(\lambda - Z) = Y_0\left[\cos\left(2\pi - \frac{2\pi Z}{\lambda_g}\right) - 1\right] \cong -\frac{Y_0}{2}\left(\frac{2\pi Z}{\lambda_g}\right)^2$$

EQUATION FOR Z

$$-\alpha(\lambda_g - Z) = -\frac{Y_0}{2}\left(\frac{2\pi Z}{\lambda_g}\right)^2 \qquad Z^2 + \frac{\alpha}{\frac{Y_0}{2}\left(\frac{2\pi}{\lambda_g}\right)^2} Z - \frac{\alpha\lambda_g}{\frac{Y_0}{2}\left(\frac{2\pi}{\lambda_g}\right)^2} = 0$$

SOLUTION OF QUADRATIC EQ $\alpha < 1$
$Y_0/\lambda_g < 1$

$$Z = \left(\frac{2\alpha\lambda_g}{Y_0}\right)^{1/2}\frac{\lambda_g}{2\pi}$$

GOOD TO 10% UPTO $\alpha \sim 10^{-1}$

THE INTERSECTION FOR RAYS BETWEEN LIMITS

$$Z = \left(\frac{2(Y(0) - \alpha\lambda_g)}{Y_0}\right)^{1/2}\frac{\lambda_g}{2\pi}$$

THE TANGENT OF THE CORRUGATED SURFACE AT THE POINT OF INTERSECTION

$$\left.\frac{dy}{dz}\right|_{\text{SURFACE}} = \frac{2\pi Y_0}{\lambda_g}\sin\frac{2\pi Z}{\lambda_g} \xrightarrow[Z/\lambda_g < 1]{} \left(\frac{2\pi}{\lambda_g}\right)^2 Z Y_0$$

ELIMINATE Z AND GET USEFUL EXPRESSION IN TERMS OF α AND $Y(0)$

$$\left.\frac{dy}{dz}\right|_{\text{SURFACE}} = \frac{2\pi}{\lambda_g}\left(2Y_0\left(Y(0) - \alpha\lambda_g\right)\right)^{1/2}$$

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THE DISTRIBUTION OF REFLECTED ANGLES

UNIT NORMAL VECTOR TO THE SURFACE

$$\hat{n} = \frac{\hat{y} - \frac{dy}{dz}\hat{z}}{\left(1 + \left(\frac{dy}{dz}\right)^2\right)^{1/2}}$$

LAW OF REFLECTION WRITTEN IN VECTOR FORM

$$\hat{K}_{out} = \hat{K}_{in} - 2(\hat{K}_{in} \cdot \hat{n})\,\hat{n} \qquad (1)$$

DEFINE

$$\hat{K}_{out} = \sin\beta\,\hat{y} + \cos\beta\,\hat{z}$$

$$\hat{K}_{in} = -\sin\alpha\,\hat{y} + \cos\alpha\,\hat{z}$$

LOOK AT CHANGE IN y COMPONENT ONLY (TRANSVERSE) FROM EQ 1

$$\sin\beta = -\sin\alpha + \frac{2\left(\sin\alpha + \frac{dy}{dz}\cos\alpha\right)}{\left(1 + \left(\frac{dy}{dz}\right)^2\right)}$$

IN THE LIMIT

$$\frac{dy}{dz} \ll 1 \qquad \alpha \ll 1 \quad , \quad \beta \ll 1$$

$$\boxed{\beta = \alpha + 2\frac{dy}{dz}} \qquad \text{(AS EXPECTED)}$$

$$\beta = \alpha + \frac{4\pi}{\lambda_g}\left(2y_0\,|(y(0) - \alpha\lambda_g)|\right)^{1/2}$$

REDISTRIBUTION : BEAM AT INPUT ANGLE α

GETS REDISTRIBUTED $\quad \alpha \leq \beta \leq \alpha + 4\pi\left(\frac{2y_0}{\lambda_g}\right)^{1/2}\alpha^{1/2}$

42.381 50 SHEETS 5 SQUARE
42.382 100 SHEETS 5 SQUARE
42.389 200 SHEETS 5 SQUARE
NATIONAL

FOR CORRUGATED PIPE WITH

$y_0 = 1.27$ cm

$\lambda_g = 12.7$ cm

$$\beta_{max} = \alpha + 5.62\,\alpha^{1/2}$$

α	β_{max}
10^{-2}	0.57
3×10^{-3}	0.31
10^{-3}	0.18
3×10^{-4}	0.097
1×10^{-4}	0.056

THE CORRUGATIONS CERTAINLY DO A JOB ON THE "GRAZING INCIDENCE RAYS

REDISTRIBUTION OF AN INPUT BEAM BY THE CORRUGATIONS

THE PROBLEM IS ONE DIMENSIONAL SINCE ONLY THE TRANSVERSE ANGLES ARE REDISTRIBUTED.

THE REDISTRIBUTION IS ALWAYS TOWARD LARGER ANGLES BECAUSE OF THE SHADOWING BY THE CORRUGATIONS, EXACTLY THE RIGHT WAY TO INCREASE THE OVERALL ATTENUATION BY THE TUBE FOR GRAZING RAYS.

THE EXACT CALCULATION OF THE PROPAGATION ALONG A CORRUGATED TUBE SEEMS DIFFICULT FOR ME SO I WILL APPROXIMATE BY ASSUMING THAT THE REDISTRIBUTION TAKES PLACE UNIFORMLY OVER THE BAND OF ANGLES $\Delta\beta$

$$\Delta\beta = 4\pi \left(\frac{2y_0}{\lambda_g}\right)^{1/2} \alpha^{1/2}$$ IN ONE DIMENSION

BUT WITH NO REDISTRIBUTION IN THE ORTHOGONAL DIRECTION

THE TOTAL TWO DIMENSIONAL BEAM ATTENUATION FOR RAYS AT ALL INCIDENCE ANGLES $\alpha \leq \alpha_0$ WILL BE APPROXIMATELY GIVEN

BY $$\left(\frac{\alpha_0}{\Delta\beta}\right)^{1/2} = \left[\frac{\alpha_0^{1/2}}{4\pi(2y_0/\lambda_g)^{1/2}}\right]^{1/2}$$ PER ENCOUNTER WITH THE CORRUGATED TUBE

THE ATTENUATION FROM MULTIPLE ENCOUNTERS WITH WALLS IS GIVEN AS BEFORE (RW P3, P10)

$$\text{ATTENUATION}(\alpha > \alpha_0) = \left[\left[\frac{\alpha_0^{1/2}}{4\pi\left(\frac{2y_0}{\lambda_g}\right)}\right]^{1/2}\right]^{\frac{L\alpha_0}{2R}}$$

WITH THE PARAMETERS

$y_0 = 1.27$ cm

$\lambda_g = 12.7$ cm

$L = 4$Km $= 4\times10^5$ cm

$R = 61$ cm

α_0 (RAD)	ATTENUATION db IN 4Km
1×10^{-2}	242
8×10^{-3}	240
6×10^{-3}	186
4×10^{-3}	130
3×10^{-3}	101
2×10^{-3}	70
1×10^{-3}	37.5
8×10^{-4}	30.6
6×10^{-4}	23.6
4×10^{-4}	16.3
2×10^{-4}	8.6
1×10^{-4}	4.6

CORRUGATED TUBES LOOK VERY GOOD IN REDUCING THE CRITICAL ANGLE FOR 80 db ATTENUATION ALONG THE 4Km TUBE.

THEY ARE NOT BY THEMSELVES GOOD ENOUGH TO ELIMINATE THE NEED FOR BAFFLES. AS CAN BE SEEN FROM THE TABLE ABOVE RAYS AT α ANGLES $\alpha < 2\times10^{-3}$ RADIANS MUST STILL BE BLOCKED BY BAFFLES.

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