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GLAST Tracker Structural Material Selection

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1 Introduction

It has long been understood that a pair conversion telescope such as GLAST will give the best performance if the converter material is localized in thin planes placed above and as close as possible to the detector planes. Additional material placed in other locations, for purposes of structural support or electronics readout, results in photon conversions that are relatively poorly measured. For that reason, in the original GLAST design beryllium was chosen for the structural elements of the tracker. Eventually it was realized that carbon-composite materials could yield structures that are just as transparent, for a given strength, while solving problems with thermal expansion, thermal conductivity, and the high cost of working with beryllium.

The current baseline design of the tracker mechanical structure is based nearly entirely on carbon composites. The tray panels are composed of honeycomb cores and face sheets made from GFRP (carbon fibers held in a cyanide-ester resin). GFRP C-channels close out the panel, and details for corner posts and mounting of electronics and walls are made from machined carbon-carbon material and bonded to the closeouts. Either GFRP or carbon-carbon material is used for the tower walls. Figure 2.1.1 shows photographs of the carbon-fiber tray prototype recently developed by Hytec, using funding from a D.O.E. Phase-1 SBIR. A complete report on this development effort is available: HTN-102021-0001 on http://scipp.ucsc.edu/groups/glast/mechanical/HTN-102021-0001.pdf.

Figure 2.1.1. Photographs of the Hytec carbon-fiber tray prototype, constructed with SBIR funding.

Figure 2.1.2. The aluminum-closeout tower built by Hytec with NASA SBIR funds to validate the GLAST structural design concept.

On the other hand, the BTEM tracker was developed using aluminum closeouts and aluminum walls. That, however, was not a space-qualified design. In particular, the carbon-fiber face sheets were too thin (75 μm) to prevent trays from hitting each other during launch and to prevent excessive thermal stress on the detector payload. Hytec also built an aluminum-closeout tower, with 10 layers, for a NASA Phase-1 SBIR. See Figure 2.1.2. It employed heavier carbon-fiber face sheets and was demonstrated to pass the vibration testing needed for space qualification. This tower was built to validate the structural design concept—the intention at the time was that the flight version would not employ aluminum.

The present dilemma is that the projected development costs to complete the carbon-fiber design and the costs to manufacture the carbon-fiber trays both greatly exceed the allocations in our proposal. Apparently, the only cost-effective alternative in hand is a design based on aluminum closeouts and aluminum tower walls, although a simpler carbon-fiber tray design is presently being investigated. Unfortunately, changing to aluminum would more than double the material, in radiation lengths, between the active volume of one tower and that of the next, and it would also significantly increase the mass of the tracker. The purpose of this note is put together information necessary to make a choice between these three options:

- ☐ continue the carbon-fiber-structure development program already in progress,
- ☐ or switch to development of a more simple but heavier carbon-fiber tray,
- ☐ or revert to the aluminum closeout design, probably also with aluminum side walls.

2 Major Issues for Consideration of Aluminum vs. Carbon

2.1 Tower Cooling

In the proposal we specified a temperature drop from the top of a tower to the bottom of 7ºC, with a maximum temperature at the top of the hottest tower of 25°C. The heat load from a single readout module is estimated by taking the presently known electronics power dissipation of 210 μW/ch plus 30% contingency and multiplying by 1536 channels, to get 0.42 W. Table 2.2.1 shows some estimates of the temperature drop for four different materials. Evidently, with 1.5 mm walls the 7ºC goal can be achieved only with the most advanced GFRP, K1100/CE, which we already determined several months ago to be too costly for the tracker budget, at >$5000 per tower side. Therefore,

Table 2.2.1. Estimates of the temperature drop from the top of a tracker tower to the bottom, assuming 0.42 W of power per readout section and 36 readout sections per tower. The walls are assumed to be 37 cm wide and 1.5 mm thick. These were obtained by rescaling the Hytec FEM results for power and width but are readily verified to good accuracy by hand calculation, due to the simple geometry. For the carbon-based materials the conductivity depends on how the fibers are oriented in various layers.

Wall Material	**Assumed Conductivity**	**Temperature Drop**
Aluminum Alloy (6061-T6)	167 W/mK	13.4° C
GFRP K1100/CE	360 W/mK	6.2° C
GFRP YS-90A/CE	180 W/mK	12.7° C
Carbon-Carbon P30	240 W/mK	9.5° C

we must be prepared to relax the requirement somewhat. That either reduces the detector noise margin at end-of-life or else places more stringent requirements on the cooling system, in order to keep the top of the grid below about 12°C, for example, in case that aluminum is used. (How much cost could potentially be saved in the cooling system by paying for K1100 fibers in the tracker is unknown.)

2.2 Inter-Module Material

Detailed information is available from which the radiation lengths of material between active volumes of adjacent tower modules can be estimated. The aluminum closeout design is assumed to be identical to the BTEM prototype, but scaled up to the final size. The electronics material is based on measured BTEM modules (see http://scipp.ucsc.edu/groups/glast/electronics/Electronics_Mass.pdf), and the average thickness in R.L. is assumed to be the same as for the BTEM. The carbon-fiber tray material is based on the Hytec prototype.

The following detailed assumptions are made in order to estimate the radiation lengths of material encountered by a particle passing from one tower to the next, perpendicular to the wall:

- Closeout masses based on Hytec designs of a 40 cm tower: Al 275 g; C 140 g
- Radiation lengths: Al 24 g/cm^2; C 42.7 g/cm^2
- Electronics board: 1.35% R.L. over an area of 67.8 cm^2 gets averaged over two full tray sides
- Backing plate: 0.04 cm of G10 under each electronics board.
- 1.5 mm thick tower walls, regardless of what material is used.
- The material is assumed to be uniformly distributed over the tower side. This would be approximately true *only* if the tower orientation were alternated from one tracker module to the next, in order that circuit boards on one tower do not coincide with

Table 2.2.2. Accounting of the radiation lengths between active volumes of two adjacent tracker tower modules, for aluminum and carbon-fiber designs.

	Aluminum	Carbon Fiber
Closeout	2.2%	0.64%
Circuit board	0.43%	0.43%
Backing plate	0.07%	0.07%
1.5 mm thick wall	1.7%	0.65%
Total	4.4%	1.8%

those of its neighbors (this may be a good requirement to place on the design).

Hence the total amount of material traversed by a particle going from the active volume of one tower to the active volume of a neighbor would increase from 3.6% R.L. to 8.8% R.L. in going from the current carbon-fiber design to an aluminum design. This situation might be improved somewhat by further lightweighting of the aluminum closeouts (or perhaps substitution of magnesium for aluminum), but that in itself would require some further development expenditures. An increase in material has important performance implications, which are explored in Section 4. It should be noted that the simulations used to derive the performance parameters presented in our NASA proposal included 4.4% R.L. of material (carbon and beryllium) between towers.

2.3 Thermal Expansion

The increase in material in going to an aluminum closeout option would not be as severe if carbon-fiber walls could still be used. The problem is that the aluminum closeouts would expand and contract along the width of the tower with changing temperature. In addition, the height of the entire tower stack is determined by the stacking of the aluminum closeouts with metal spacers in between, so the height is not thermally stable. It is highly questionable whether thermally stable carbon-fiber walls could be attached to the aluminum structure without crushing the walls around the fasteners during temperature cycling.

Furthermore, if there is a horizontal temperature gradient across a tower, then it will distort, possibly enough to affect the alignment. This issue would have to be quantitatively evaluated in the case of an all-aluminum design. The grid will naturally produce such gradients, and possibly the outermost towers will each be hot on the side facing the ACD. To estimate the possible severity of this issue, consider a 5°C temperature difference from one side of a tower to the next. With aluminum this would result in one side being about 70 μm taller than the other. In terms of tower tilt this roughly corresponds to 20 arc-seconds, which is of the order of magnitude of our calibration goal.

At the tray level in the aluminum closeout option there is a thermal (and chemical) mismatch between the closeout and carbon-fiber face sheet (we judge an aluminum face sheet to be unacceptable). This raises three issues that will require some investment in engineering if an aluminum design is chosen:

- Corrosion. This issue can probably be avoided by controlling well the adhesive thickness and anodizing the aluminum.
- Strength of the adhesive bond. Hytec has done a quick experiment with trays from the NASA SBIR tower (Figure 2.1.2). A few of those trays have heavy carbon-fiber face sheets, loaded with lead and dummy silicon payload, bonded to aluminum closeouts. They cycled a tray 8 times through our required test range (–30°C to 50°C) and found some debonding of the face sheet from the closeout. Further temperature cycling is in progress to see how the debonding propagates.
- Stress on the silicon payload. We have found that thin lead converters bonded to a carbon-fiber tray should produce negligible mechanical stress in the detectors when cycled through our test range (this will be verified soon in tests). Aluminum closeouts would greatly increase the stress in the edge detectors, possibly to dangerous levels. With thick-converter trays, the converter itself produces a

significant thermal mismatch, which we intend to try to correct by the use of compliant adhesives and a different converter material (probably tungsten). Reliance on compliant adhesives would probably also be necessary for the thin-converter layers in the case of an aluminum closeout (see Figure 2.3.1 for an illustration of the tray distortions).

On the other hand, an aluminum design would reduce the thermal mismatch between the tracker and grid, which would simplify somewhat the engineering of that interface. Even so, bolting the grid securely to the closeout of the bottom tray will increase the stress on the bond between closeouts and face sheets, further complicating that issue.

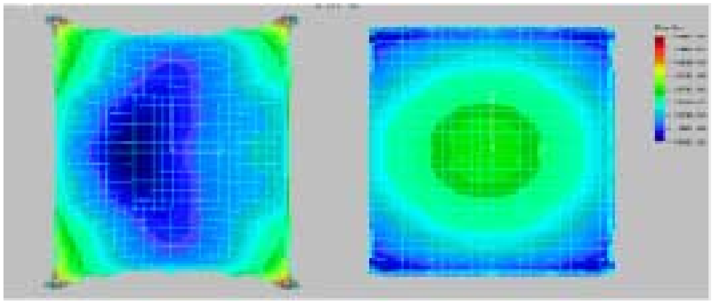

Figure 2.3.1. Simulations of the tray distortions caused by an aluminum closeout with a 20°C temperature change (left) compared with a carbon-fiber tray (right).

2.4 Instrument Mass

For 37-cm towers the aluminum closeout weighs about 0.125 kg more than the carbon-fiber version.[1] That corresponds to a 38 kg increase for the instrument mass. Assuming a density of 1850 kg/m^3 for GFRP material versus 2700 kg/m^3 for aluminum, each tower wall would increase in mass by 0.292 kg, to give a 19 kg increase in instrument mass. Thus the total increase in instrument mass would be about 57 kg if we chose the aluminum option. For comparison, removal of two upper layers from the tracker would save about 45 kg. Removal of a single thick-converter layer would save about 58 kg, assuming 25% R.L. converters. (Here it is assumed that the converter material in the layers removed is not added back into the remaining layers.)

It should also be pointed out here that our solution to the CTE mismatch problems in the thick-converter layers will likely involve the use of tungsten converter, which carries a 6% mass penalty, compared with lead. That adds up to 8.2 kg of extra mass, assuming the likely case that lead is still used in the thin-converter layers.

3 A Simplified Carbon-Fiber Design

Recently it has been realized that the costs and risks associated with a carbon-fiber closeout could be reduced by simplifying the design. The idea is to make the closeout from four pieces of carbon-carbon material that are pre-machined. They would then be bonded to the core and face sheets, yielding a tray that would not require a large amount of finish machining. This has several advantages over the current carbon-fiber design:

- ☐ The machined carbon-carbon surfaces could be passivated before assembly by relatively simple and standard methods. The machining would actually be simplified with respect to the 1-piece aluminum closeout used in the BTEM.
- ☐ The number of pieces that need to be bonded to the tray is greatly reduced with respect to the existing design, significantly reducing fabrication costs.

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[1] The Hytec estimate is 275 g for a 40-cm Al closeout and 140 g for a carbon-composite closeout. I scaled the difference by 37/40 to arrive at the 125 g estimate.

The main disadvantage with respect to the existing carbon-fiber design is that the weight would likely be close to that of the aluminum closeout. Another disadvantage is that it is a new design that needs significant work to bring it to the level of the existing design.

The simplified carbon-fiber design would retain significant advantages over the aluminum-closeout option:

- The number of radiation lengths in the closeout would be about half that of the aluminum design.
- Carbon-fiber tower walls could be used, greatly reducing the radiation lengths and also saving on mass and possibly improving cooling.
- There would be less stress in the silicon detectors during temperature excursions.
- There would be much less thermal distortion of the tower alignment.

The issues associated with the three design choices are summarized in Table 2.4.1.

Table 2.4.1. Summary of the issues associated with the three design concepts.

	Carbon[1] (Baseline)	**Aluminum[2]**	**Simplified Tray[3]**
Structural Materials	▪ GFRP and carbon-carbon closeouts ▪ GFRP facesheet ▪ GFRP core	▪ Aluminum closeout ▪ GFRP facesheet ▪ GFRP core	▪ Carbon-carbon closeout ▪ GFRP facesheet ▪ GFRP core
Performance	Best	≈10% worse tails in PSF	Intermediate
Mass compared with proposal baseline[4]	Low ~9 kg under budget	High ~48 kg over budget	Moderate Close to budget
Radiation lengths in average wall thickness	Low (42.7 g/cm^2,1.8% total)	High (24 g/cm^2, 4.4% total)	Moderate (42.7 g/cm^2, 2.4% total)
CTE Effect on Dimensional Stability	Low ($\alpha=-1.2\times10^{-6}$/°C)	Very High ($\alpha=23.6\times10^{-6}$/°C)	Low ($\alpha=-1.2\times10^{-6}$/°C)
CTE Mismatch – Silicon and Tray	Low (Reduced stress in silicon)	High (Increased stress in silicon)	Low (Reduced stress in silicon)
Thermal Conductivity	Adequate[5] (ΔT = 12.7°C)	Adequate (ΔT = 13.4°C)	Adequate[5] (ΔT = 12.7°C)
Schedule Impact	Moderate	Low	Moderate
Approx. % Developed	40	45	30
Tray Prototyped	Yes – (one)	Yes – (several)	No
Sidewalls Prototyped	In Process	Yes	In Process
Cost Risk	High	Moderate	High

1. Baseline Design Concept: Carbon fiber sidewalls, face sheets, honeycomb core and lightweight closeout frame.
2. Aluminum Design Concept: Aluminum sidewalls and closeout frame, carbon-fiber face sheets, and aluminum or carbon-fiber honeycomb core.
3. Simplified Tray Design Concept: Carbon fiber sidewalls, face sheet and honeycomb core, with a heavier but simpler and cost effective closeout frame. Development costs are expected to be as high as the Baseline design concept due to limited development to date. Substantial cost savings will result in the flight hardware fabrication.
4. The AO proposal mass budget for the tracker mechanical structure is 191 kg, which will be reduced by a few percent given the recent change in tower size from 38 cm to 37 cm.
5. This assumes the low-cost composite YS-90A/CE. The 7° temperature-drop goal in our NASA proposal could only be reached with a high-price composite such as K1100/CE.

4 Remaining Tower Mechanical Engineering Issues and Tasks

The following is a list of issues that remain to be addressed in the tower mechanical engineering effort. It is assumed that issues associated with the fabrication of the payload (converters, detectors, and circuits) will be handled by SLAC, UCSC, and INFN, so they are not listed here.

4.1 General

- Completion of the tray design, including some further numerical analysis, optimization of the face sheet and core material, adhesive selection and bond-joint design, inserts as required, and finish coating as required.
- Design of the bottom tray and the interface with the grid. This includes dealing with a CTE mismatch, even in the case of an aluminum closeout (since the face sheet still is carbon-fiber).
- Design of the top tray (slight variations from the other trays).
- Design of clips to connect towers and snubbers for the interface with the ACD. Substantial numerical analysis of multiple towers will be required.
- Adhesive selection and detailed bond-joint design for tray fabrication.
- Completion of the sidewall design, including material selection, testing of coupons, fastener choice and design (inserts if needed).
- Prototyping of trays and other components.
- Design validation for space flight by analysis and testing.
- Documentation of the design and interfaces.

4.2 Carbon-Fiber Design

- Potential release of carbon particles. This most likely requires a coating to be developed.
- Threaded connections in the closeout will require inserts bonded into the carbon-fiber parts before machining.
- Carbon-fiber sidewalls may require inserts. Whether inserts may be avoided in this case has yet to be studied.
- Some development is required to ensure adequate venting of trapped air volumes.

4.3 Simplified Carbon-Fiber Design

- Potential release of carbon particles. Again, a coating would need to be developed. However, in this case the closeout parts probably could be coated by a standard immersion technique before assembly.
- Inserts for threaded connections.
- Inserts for carbon-fiber walls.
- This closeout is only at the level of a concept under investigation and would require a new design and development effort.

4.4 Aluminum Design

- CTE mismatch between the face sheet and closeout. Development of a bond that can withstand and/or decrease the stress would be required.

- Thermal distortion of the tray. More effort would be needed in the development of a compliant bond between the tray and the silicon to insure that the detectors are not damaged during thermal cycling.
- Thermal distortion of the tower. Misalignment on the order of hundreds of microns is possible. Some analysis will be required to understand and characterize these effects. Correction of the effects can likely only be done at the data analysis level.
- Threaded connection may require inserts. In this case the inserts could be threaded in (helicoil).
- Chemical mismatch with carbon. Anodizing of the aluminum will probably be required.

5 Performance Implications

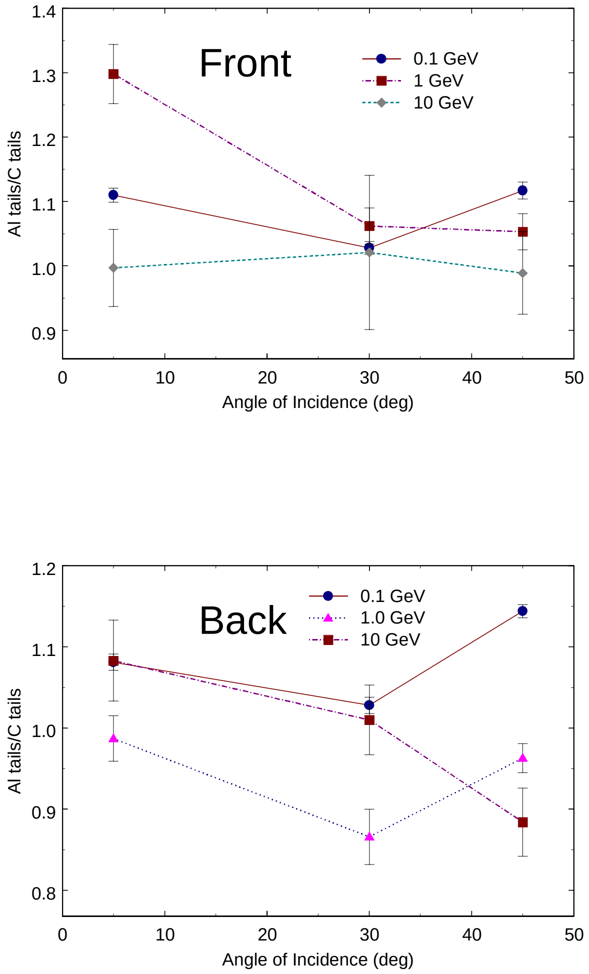

Figure 4.4.1. Ratio of PSF tails in the Aluminum design to those in the Carbon design. The ratio of the 95% to 68% width of the PSF is used as a measure of the tails.

5.1 Point Spread Function

The wall and closeout material is expected to impact the point spread function primarily by contributing to the non-gaussian tails. Conversions that occur in the tower fiducial volume can be impacted if one or more of the conversion products passes through the walls shortly after the conversion. That is fairly likely to occur for photons that are away from normal incidence. However, tracks from conversions near normal incidence can have a very large amount of wall material to traverse. Conversions that occur in the wall material itself are likely to be poorly measured due to the large lever arm from conversion point to the first measurement. However, to some extent such conversions can be eliminated from the data sample.

In Figure 4.4.1 the PSF tails are compared between the aluminum option versus the baseline carbon option (which closely corresponds to the configuration in our NASA proposal). For the Back section (thick converter layers) we expect it to be unlikely that the wall material will have an easily noticeable effect when combined with 25% converter foils. In fact the results scatter on both sides of unity. The scatter is larger than the statistical error bars. Nevertheless, there does not seem to be any logical pattern.

For the Front section the results consistently indicate that the aluminum option has worse tails. However, either the pattern is not consistent, indicating a scatter larger than the error bars, or else there are effects present that we don't understand. In particular, the large effect near normal incidence at 1 GeV does not naïvely seem consistent with the 0.1 GeV and 10 GeV points.

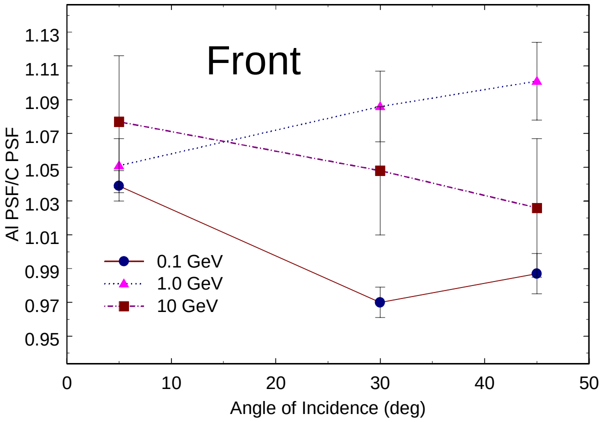

Figure 5.1.1. The ratio of angular resolution in the Aluminum design compared to the Carbon design. The 68% width of the PSF is used as a measure of angular resolution.

Figure 5.1.1 compares the PSF 68% width between the aluminum and carbon designs. There is no obvious trend in the results, so as expected the wall material does not have a significant impact on the 68% width of the PSF.

One should keep in mind that these simulations were done with the reconstruction software as it existed at the time of the formulation of our NASA proposal. If the program is refined significantly in the future, then the relative contribution of the wall material to the tails might increase.

5.2 Background Rejection

There has not been sufficient time to redo the background simulation and analysis, since that task typically takes months to complete with a new detector configuration. The increase in inter-tower material is not likely to introduce a background source that we have not seen before, since the amount of material in previous simulations was already half of the worst case considered here. The largest source of irreducible background in previous simulations was due to hadrons traversing the instrument horizontally. In that case the material parallel to the detector planes, not the wall material, is the biggest problem. Additional wall material could be a problem for hadrons near normal incidence that sneak through the ACD and interact in the wall, producing photons. Such hadrons are likely to leave additional signatures somewhere in the instrument, so in principle it should be possible to eliminate most of them with judiciously chosen cuts. The main impact on performance in the end will likely be some loss of effective area, by an unknown amount, due to the additional cuts needed to eliminate the extra background.

6 Schedule and Risk

The following is an outline of the tracker mechanical design schedule and milestones:

Begin standard tray prototype fabrication	March 1, 2001
☐ Preliminary standard tray design complete (HYTEC)	
☐ Preliminary payload design complete (SLAC, UCSC)	
Begin fabrication of engineering model	July 16, 2001
☐ Final standard tray design complete (HYTEC)	
☐ Final thick-converter tray design complete (HYTEC)	
☐ Final payload design complete (SLAC, UCSC, INFN)	
☐ Final bottom tray design complete (HYTEC)	
☐ Final sidewall design complete (HYTEC)	
☐ Preliminary tower assembly design complete (HYTEC)	
☐ Preliminary tower assembly fixture design complete (SLAC, INFN)	
☐ Preliminary tower clips and ACD support design complete (HYTEC)	
Instrument PDR	August 1, 2001
Begin engineering model testing	February 15, 2002
Instrument CDR	July 1, 2002
☐ Final tower assembly design complete (HYTEC)	
☐ Final tower assembly fixture design complete (SLAC)	
☐ Final tower clips and ACD support design complete (HYTEC)	
Begin fabrication of flight hardware	July, 2002

The schedule is very tight to complete a carbon-fiber design in time to begin building the engineering a year from now. A decision has to be made now whether to move forward with it and in what direction. If we begin going now in the direction of an aluminum design, then there will certainly be no time in the future to turn back to carbon fiber.

The carbon-fiber design has more schedule and cost risk than does aluminum. The cost of the carbon-fiber design can be reduced by simplifying the design, at the expense of some weight. That would significantly reduce the cost risk and could also reduce risk associated with developing surface passivation. Nevertheless, the development schedule would be just as tight, since it requires a new design.

7 Cost

7.1 Hytec Estimates

Table 7.1.1 shows Hytec's estimates of the remaining costs to complete the tracker mechanical structure, assuming that the payload development and payload assembly work is done elsewhere. The costs were rolled up from a detailed schedule of tasks, which has been provided to us for review but is too lengthy to include here. The development costs include design and analysis, selection of materials, fabrication and testing of material coupons, fabrication of prototype trays and other parts, and complete qualification-level testing of the prototype components. The detailed costing was done for the baseline-carbon and aluminum options. The simplified carbon-tray design was conceived to lower production costs, and for present purposes it was assumed to be just as costly to develop as the baseline, mainly because it would not benefit as much from work already accomplished. The aluminum option is not tremendously cheaper than carbon fiber mainly because either route still requires a complete effort on analysis and qualification testing.

Our NASA proposal budgets $757,000 for the Tracker-Level Engineering & Development subcontract to Hytec, of which about $150,000 appears already to be spent (the precise amount spent from this budget is unclear to me). Up to about $380,000 was budgeted for Instrument-Level Engineering & Development, of which I'm not sure how much has already been spent or reallocated elsewhere. "SuperGLAST" engineering development was not budgeted at all (See Section 7.2). $252,264 was allocated for engineering support of the Engineering-Model fabrication and testing (not including tray and tower M&S and assembly costs). This Engineering-Model engineering support will be divided between Hytec and SLAC. Clearly the biggest problem is with the Tracker-Level Engineering & Development, where even for the aluminum option there is an apparent deficit of about $500,000, including the SuperGLAST tray work. We are working with Hytec to try further to refine these estimates and remove nonessential tasks.

A detailed breakdown of the costs for procurement of the Engineering-Model and Flight-Model tower components is given as an appendix to this report. Included are the details of the corresponding costs in our NASA proposal, which add up to $1,691,106. The Hytec estimates for the aluminum option and the simplified carbon-tray option fit well within the budget, but the carbon baseline would appear to be ruled out. Note that Hytec's cost estimates for the aluminum option assume an aluminum core, but I assume that we should use, even in that case, a carbon-fiber core, which would enhance the stiffness and transparency of the tray.

Table 7.1.1. Hytec estimates of mechanical engineering support and construction costs for the remainder of the tracker program. Engineering in the formulation phase does not include work done at SLAC, UCSC, and INFN on payload engineering and assembly fixture development. Division of the engineering during the implementation phase between SLAC and Hytec remains to be determined.

Description	**Carbon (Baseline)**		**Aluminum**		**Simplified Tray**	
	Labor	**M&S**	**Labor**	**M&S**	**Labor**	**M&S**
Formulation Phase						
Tracker-Level Engineering & Development	1,234,228	144,800	965,731	87,000	1,234,228	144,800
SuperGLAST Tray Development	74,872	13,000	56,398	7,000	74,872	13,000
Instrument-Level Engineering & Development	156,152	6,000	156,152	6,000	156,152	6,000
Engineering Support of Engineering Model Fabrication and Testing	96,384	6,000	96,384	6,000	96,384	6,000
Engineering Model M&S		186,535		95,741		126,425
Implementation Phase						
Tracker-Level Engineering Support	470,100	46,200	379,090	44,700	470,100	46,200
Instrument-Level Engineering Support	59,637	12,000	59,637	12,000	59,637	12,000
Flight Tower M&S		2,236,600		920,390		1,294,480

Table 7.2.1. Somewhat more detailed breakdown of the costs for "Tracker-Level Engineering Development" in Table 7.1.1.

Baseline Carbon-Fiber	Total	Spent	Remaining
Development Costs	$1,592,134	$491,568	$1,100,566
Standard Tray & Closeout	$735,968	$124,992	$610,976
Bottom Tray	$79,959	$0	$79,959
Top Tray	$85,900	$0	$85,900
Payload integration	$143,395	$92,000	$51,395
Sidewalls	$145,149	$92,896	$52,253
Tracker	$401,763	$181,680	$220,083
Tracker Design Coordination	$193,136	$19,644	$173,492
Tracker Document Control	$52,896	$10,526	$42,370
Tracker Meetings inc. prep.	$66,464	$18,864	$47,600
Tracker Meetings M&S	$24,000	$9,000	$15,000
Total	$1,928,630	$549,602	$1,379,028

Aluminum Option	Total	Spent	Remaining
Development Costs	$1,283,933	$491,568	$792,365
Standard Tray & Closeout	$487,916	$124,992	$362,924
Bottom Tray	$69,520	$0	$69,520
Top Tray	$85,900	$0	$85,900
Payload integration	$143,395	$92,000	$51,395
Sidewalls	$133,240	$92,896	$40,344
Tracker	$363,962	$181,680	$182,282
Tracker Design Coordination	$175,040	$19,644	$155,396
Tracker Document Control	$52,896	$10,526	$42,370
Tracker Meetings inc. prep.	$66,464	$18,864	$47,600
Tracker Meetings M&S	$24,000	$9,000	$15,000
Total	$1,602,333	$549,602	$1,052,731

7.2 Implications of “SuperGLAST”

Even though the so-called SuperGLAST converter configuration was specified as the baseline in our proposal to NASA, that decision was made too late in the game to allow it to propagate through to the detailed design budgeting. Therefore, the tracker cost estimates in the proposal do not take into account any increased expenses for designing and building the hybrid tracker verses the older baseline which had the same converter thickness in all layers. It is difficult to estimate by how much, but the new design certainly does increase costs, both in development and manufacturing, and is partly responsible for the projected overrun in engineering costs. The reasons include the following:

- The analysis and design now has to be done for two very different trays: one supporting very thin converters and another supporting thick, heavy converters.
- The thick converters result in serious problems with differential thermal expansion, causing unacceptable stress in the detectors if lead is used and sufficient decoupling is not provided. We have already spent a significant amount of engineering time grappling with this issue.
- The solution to the CTE issues will likely include the use of tungsten in place of lead, which will carry at least a 6% penalty on the converter mass and will cost an estimated additional $50,000 for the raw material.

- Design, testing and qualification has to be carried out on two very different trays. This component of the additional expense is about $88,000, as indicated in Table 7.1.1.
- The number of different parts is increased, increasing bookkeeping costs and requiring more spare parts.
- The different trays will most likely have slightly different dimensions, requiring different assembly fixtures.
- Assembly of the trays will be different for the two types, increasing assembly costs.
- Other cost increases related to SuperGLAST, such as for software development, are probably also significant but do not directly concern the tracker budget under consideration here.

7.3 Possible Cost Savings in the Tracker from Descope

The overall tracker cost can be reduced by decreasing the number of layers (which would also aid the mass and power budgets). In the proposal we estimated that $700,000 is saved for each layer removed. A similar amount would be saved if the number of towers (currently 16 plus 2 spares) was reduced by one. Such savings would be difficult to apply to covering overruns in development costs, however, because the savings would occur later in the program.

8 Conclusions

It is recommended to keep a carbon-fiber based structural design, but to move to a simplified, more conservative design to reduce production and development costs. The panel core material can be aluminum, in order to save on material costs.