Tools for ZD/DR Alignment

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Abstract

Two suez modules to facilitate alignment, ZDAlignmentMod and DRAlignmentMod, are presented in three levels of detail: strategy, use, and implementation. DualTrackProd, a suez producer which implements a two-track (bhabha, μ-pair) constraint is also described, on the level of use. Three related processors/producer are also explained: ZDAlignmentBhabhaFilterProc, DRAlignmentBhabhaFilterProc, and DualTrackToUsageTagProd. This document is intended for anyone who will be globally aligning the ZD or aligning DR wedding cake rings, and will assume familiarity with suez. An alignment strategy will be described in detail, but current issues in and obstacles to alignment are not presented in this note.

Contents

1 Quick Introduction

For centuries, mankind has gazed into the stars and pondered how to align the ZD. ZDAlignmentMod is a code package that I developed to encapsulate the latest ideas on how to do this, and to automate the process once it's fully understood. DRAlignmentMod and DualTrackProd are offshoots which will probably be useful as well, for aligning the DR wedding cake (DRAlignmentMod) and for getting pairs of tracks which are constrained to be back-to-back (DualTrackProd), *with residuals.* Each will be described in a major section of this note.

ZDAlignmentMod and DRAlignmentMod are intended as works in progress: as tracking problems become understood, it will probably be necessary to change (or re-write) the code. On the other hand, DualTrackProd does a simple thing, and I think it does it correctly. Therefore, while the implemenation of the two alignment modules will be fully exposed in this document, the dual-track producer will only be explained from a user's perspective.

2 ZDAlignmentMod (and ZDAlignmentBhabhaFilterProc)

2.1 ZDAlignmentMod Strategy

"ZD or DR Alignment" here means to find the real orientation of the ZD, or of subcomponents of the DR, relative to the DR stereo section which defines the CLEO coordinate system. The true orientation may be different from the orientation assumed in track reconstruction, which may lead to tracking biases. These kinds of biases are easiest to see in bhabha or μ-pair events, where the final state is easy to anticipate: two nearly straight tracks originating from a common point, recoiling at beam energy in opposite directions.

For ZD alignment, we are interested in determining the orientation of a small detector (the ZD) with respect to a large, existing one (the CLEO-III central drift chamber). We can do this most cleanly by telling the track fitter to not use ZD hits in the track fit. We still want to know which hits are associated with a given track (which is a part of track finding), and we will want to calculate how close the fitted track comes to the those ZD hits. These differences are known as "residuals" and are defined as the distance of closest approach of the electron's or muon's track to the wire, measured by drift time (here usually called "drift"), *minus* the reconstructed helix's prediction of that distance (distance of closest approach, or "dca"). The distribution of these residuals, plotted with respect to θ or ϕ, can usually be interpreted as a geometric misalignment.

This is what ZDAlignmentMod does: it loads into memory a large sample of bhabha tracks, fit only to DR hits, along with their associated ZD hits. For a given trial ZD alignment, it will plot distributions of residuals as functions of θ, ϕ, drift, and ZD layer. If the user sees an obvious misalignment in these plots, e can adjust the alignment parameters until the deviations are minimized. ZDAlignmentMod also calculates the total root mean square residual and passes that value to MINUIT, so that MINUIT can automatically adjust alignment parameters to find the precise minimum. If the ZD calibration (drift functions and T0s) is also correct, this procedure will find the correct ZD alignment, and the RMS residual will be the intrinsic resolution of the ZD.

2.1.1 Dual-Track Constraint

The tracks used are "dual-constrained," that is, we take advantage of the back-to-backness and common origin of bhabha electrons as an additional constraint in their fit. After the two tracks have been fitted to the DR and assigned error matrices, we find the optimal track-pair which satisfies these relations:

- the impact parameters d_0 (X-Y plane) and z_0 are the same for each track (with opposite signs for d_0),

- the total transverse momentum is consistent with crossing angle (incident beams are crossed a few milliradians in the XZ plane), and
- the total longitudinal momentum is zero, because CESR collides beams of equal energy.

This dual-track is obtained from the two fitted tracks by shifting their least well determined parameters most, and a χ^2 for the dual fit represents the consistency of the two original tracks with the result. Most often when the two tracks are inconsistent with the resulting dual-track (the dual-$\chi^2 \gg 1$), it is because they had to be tilted too much in θ to satisfy the longitudinal momentum constraint. This is not surprising, as bhabhas can radiate a photon in the initial state, and this momentum loss is usually along the beam axis. The χ^2 from the dual-constraint is used to select bhabhas with little radiation.

Dual-tracks are preferred for ZD alignment because track projections to the ZD are an interpolation in the middle of a dual-track, but extrapolations on the end of an ordinary singly-fitted track. Since the dual-track is constrained by DR hits on both sides of the ZD, the dual-track has a smaller error on an event-by-event basis and an additional symmetry which might cancel unknown biases in DR track fitting. To get dual-tracks for other applications, the algorithm has been packaged into DualTrackProd (see Section 4 on page 20).

2.1.2 Use ChisqFitProd for tracks

Another strategy to reduce DR track fitting biases is to use ChisqFitProd, rather than the usual Kalman fitter. ChisqFitProd fits tracks to simple helices by minimizing their χ^2, and doesn't have a hit-order dependence like the Kalman fitter does. (One bias was observed in ZD residuals relative to Kalman fits: tracks that passed through a different number of DR superlayers had systematically different ZD residuals. This bias was not present in ChisqFitProd-fitted tracks.)

2.1.3 Bhabha Event Selection Criteria

An auxiliary processor, ZDAlignmentBhabhaFilterProc, was built to define bhabha events. The cuts are typical, but chosen to be tight. We require:

- exactly two "good tracks," with oppositely-signed charge,
- $|(d_0)_1 + (d_0)_2| < 0.5$ mm,
- $|(z_0)_1 - (z_0)_2| < 1.5$ cm,
- $(\vec{p}_1 + \vec{p}_2)_\perp < 2\%$ of beam energy, and
- $(\vec{p}_1 + \vec{p}_2)_{||} < 2\%$ of beam energy.

A "good track" is defined as one which:

- successfully fit,
- with $\chi^2/\text{DOF} < 10$,
- number of layers hit / expected between 0.5 and 1.2,
- $|d_0| < 5$ mm,
- $|z_0| < 5$ cm,

- $|\vec{p}|$ between 90% and 110% of beam energy,
- $|\cot\theta| < 2.4$,
- ${\sigma_{\cot\theta}}^2 < 0.5\ m^2$ and ${\sigma_{z_0}}^2 < 0.25\ \mathrm{m}^2$,
- with at least one ZD hit.

ZDAlignmentMod additionally requires $|\cot\theta| < 2$ and a dual-$\chi^2 < 20$. This last cut removes many bhabhas with initial state radiation. (This doesn't introduce a bias because CLEO-III sees the same distribution of +Z ISR bhabhas as -Z ISR bhabhas.)

All of these selections are made to tracks which *did not* include ZD hits in the fit.

2.1.4 ZD Hit Corrections

After ZD hits have been associated with a track, they are additionally corrected for the bhabha electron's flight time from the origin to the hit location and the time for the signal to propogate along the ZD wire. These are nanosecond-scale corrections on 0.1 microsecond drift times, and involve no tunable constants. They are applied in ZDAlignmentMod, just before calculation of the residual.

2.1.5 ZD Hit Selection Criteria

Right now, ZDAlignmentMod also removes some ZD hits before plotting them or using them for alignment optimizations. Hits are dropped if they are labled by the track finder as `kDO_NOT_FIT`, all hits on layers 1 and 6 are dropped (edit ZDAlignmentMod.cc:609 to change this), hits closer than 1.5 mm or further than 3.8 mm to the wire are dropped (set the parameters minDrift and maxDrift to change this), and a few wires are singled out as bad and therefore dropped (edit ZDAlignmentFcn.cc:357 to change this).

Layer	Bad wire (as numbered by `wireInLyr()`)
4	1, 5, 6, 8, 27, 31, and 43
5	19 and 54;
6	11

2.2 ZDAlignmentMod Use

Even though these modules might someday find their way into a fixed release, it is a good idea to check them out of the repository so that you can make changes to the code. For ZD alignment, check out ZDAlignmentMod and ZDAlignmentBhabhaFilterProc. If you are using the Oct15_03_MC release or earlier, you will also need to check out HbookHistogram and HbookHistogramModule to get a necessary bug fix to histogram resetting. (Compile HbookHistogram first.) The Qt version (how the interactive histograms look) also changed after Oct15_03_MC, so you can pick your favorite.

2.2.1 Running ZDAlignmentBhabhaFilterProc

The alignment process has been split into two stages for efficiency: DR track finding/fitting, and ZD hit residual calculation. The first stage is run once: fill PDS files with ZD hits and DR tracks in batch jobs using ZDAlignmentBhabhaFilterProc, massively in parallel. The second stage is done inside ZDAlignmentMod iteratively, using different trial alignments. So before you can do an alignment, you need to set up many jobs to collect tracks and hits, and possibly run them overnight. Look in ZDAlignmentBhabhaFilterProc/Test/sample.tcl for hints in setting up your tcl files. The key issues you will need to keep in mind are:

- Use the DR/ZD calibration of your choice, including the latest fittingweights, when they become available.
- Select ChisqFitProd, rather than KalmanProd. This is tricky if you are using $C3_SCRIPTS/trackingDataFull.tcl, since it automatically loads KalmanProd. Do this for safety:

  ```
  prod sel ChisqFitProd
  run_file $env(C3_SCRIPTS)/trackingDataFull.tcl
  prod desel KalmanProd
  ```

  It is important to load ChisqFitProd's symbols before KalmanProd gets a chance to load its own, so that you can be sure it really is ChisqFitProd that is running.
- To remove ZD hits from track fitting, use this trick:

  ```
  param ChisqFitProd ForceZDFittingWeight true
  param ChisqFitProd ZDFittingWeight 1e-10
  ```

  Technically, the ZD hits are still used in the track fit, but their weight is so small that it doesn't matter. One could also inflate the values in the constant ZDWeight2LayerDriftEntAng: this would have the same effect. (The "fittingweight" given as a parameter is loose when small, while the "fittingweight" given in ZDWeight2LayerDriftEntAng is loose when large. This is a failure of our terminology: the values in ZDWeight2LayerDriftEntAng are actually resolutions, in units of length, while the ChisqFitProd parameter takes a weight, in units of 1/length^2.)

  There are another two parameters, UseZDStereoU and UseZDStereoV, but these will actually remove the hits from the track lattices so they can't be found by ZDAlignmentMod for residual calculations. Don't use them.
- These additional producers will be necessary to do tracking on ZD data:

  ```
  prod sel AZDGeomProd
  prod sel ZDGeomProd
  prod sel CalibratedZDHitProd
  prod sel ZDDriftFunctionProd
  prod sel ZDHitCorrectorProd
  prod sel CesrBeamEnergyProd
  prod sel DBEventHeaderProd

  param DetectorConfigurationProd Override true
  param DetectorConfigurationProd UseZDnotSI true
  param DRHitCorrectorProd ApplyEntranceAngleCorr true
  param DRHitCorrectorProd ApplyStandardCorrections true
  ```

I expect trackingDataFull.tcl will soon include these, with the possible execption of the DR hit corrections. (In the CLEO-III trackingDataFull.tcl, DR hit corrections were turned off by default.)

- Include enough data for ZDAlignmentMod to be able to run. The minimum set of objects is
  - FAItem<DBEventHeader>
  - FAItem<DBTrackerValues>
  - FATable<TRTrack>
  - FATable<TRHelixPionFit>
  - FAItem<SeedTrackZDHitLattice>
  - FATable<CalibratedZDHit>

  Tcl code to do this is provided in ZDAlignmentBhabhaFilterProc/Test/sample.tcl, though this includes more data in the PDS file than the minimal set above.

  (This was part of an attempt to include enough data in the PDS files to reconstruct ZD hits at the ZDAlignmentMod level (so that the user doesn't need to re-run tracking to include new ZD calibrations). I haven't found a way to get it to work, but it is a worthwhile goal.)

2.2.2 Running ZDAligmentMod

Once you have a repository of fitted tracks on a large disk somewhere, alter ZDAlignmentMod/Test/align.tcl such that it points to your PDS files. With early CLEO-c run lengths and cosmic ray backgrounds, four runs will give you enough data for an exploratory alignment (meaning: you have to wait ten seconds between iterations—the limit of my interactive patience).

You will need to set an initial ZDGeomAlignment file, e.g. from the database:

`http://www.lns.cornell.edu/restricted/CLEO/CLEO3/soft/Constants/`,

and point ZDAlignmentMod at it using the "geom" parameter. Because I didn't remove all of my experiments, you will also need to fill a file named `normal.azdgeomlayer` with the default values of AZDGeomLayer. ZDGeomAlignment is the one that contains ZD alignment information; AZDGeomLayer defines things like wire layer radii and should not be changed. (If you don't want to call it `normal.azdgeomlayer`, you will need to set ZDAlignmentMod's "geomLayer" parameter.) If you use the above website to get a constants file, it probably set the validity range (first two numbers) to "0 0" (valid for no runs). Set it to "1 0" (valid for all runs).

Now run `suez -f align.tcl`.

Once suez has loaded everything, type `iterator go`. This opens a HistogramViewer window with seven plots to help you with alignment. Close the "instructions" subwindow (those instructions don't apply to ZDAlignmentMod, anyway) and open histogram subwindows with the heirarchy on the left by double-clicking. Arrange the subwindows now, becuase unlike HistogramViewerProc, you won't get a chance to move them again later. The "Update Frequency" field is meaningless for ZDAlignmentMod, as is the "Interact" button. The "Continue" button is used once: after you are happy with the arrangement of histograms and would like to start aligning.

Once you press "Continue," the module will load the tracks and hits from the PDS files and store them in memory. This is the last massive memory allocation: if you don't have enough memory, the module will crash here, not later. Once everything is loaded, MINUIT will go into interactive mode. From here, any MINUIT command may be executed.

MINUIT's function FCN is set to do the following:

- For each (dual-constrained) track, project the track into the ZD and calculate the residual difference between measured and predicted drift distance, using the current trial ZD geometry.
- Fill profile histograms that plot this residual as a function of θ, ϕ, drift, and ZD layer.
- Calculate the root-mean-square residual in millimeters and serve this as FCN's return value.
- Draw all of the plots in the HistogramViewer window.

Unfortunately, it is not easy to add commands to MINUIT to break up these functions into separate commands, so if a window (or a screensaver) covers the HistogramViewer window, you will need to recalculate all residuals to redraw the plots. Also, MINUIT doesn't call FCN unless it expects FCN's return value to change, so sometimes you may need to set a parameter value without changing it to force a redraw.

Interactive MINUIT commands are documented on this webpage:

`http://wwwasdoc.web.cern.ch/wwwasdoc/WWW/minuit/minmain/chapter2_8.html`

but the most useful ones are these:

- `show par` — Print current parameter values and call FCN
- `set par` N x — Manually set parameter number N to value x.
- `fix` N — Freeze a parameter so that it won't be varied in automatic optimization.
- `rel` N — Release a parameter for automatic optimization.
- `mini` — Let MINUIT vary all free parameters to minimize FCN, the root-mean-square residual. This does a little more than you want: it calculates "errors" for each parameter as though the RMS residual were a χ^2.

  (This is why residuals are reported in millimeters: the residual RMS should be $\mathcal{O}(1)$ like a χ^2. If residuals were reported in meters, MINUIT would take longer to calculate the meaningless "errors.")

2.2.3 How to interpret the MINUIT parameters

There are thirteen parameters, but normally you should only use the first six. These six describe the orientation of the ZD detector, in this order:

1. `x` is the offset of the ZD with respect to the center of the DR stereo section, in the direction parallel with the ground and perpendicular to the beamline. MINUIT is given this parameter in millimeters, so if you `set par 1 0.1`, you will set `x` to 100 microns, not 10 centimeters. (Positive offsets are away from the CESR ring, negative ones are toward the ring's center. Not that it matters.)

2. **y** is the vertical ZD offset, also in millimeters, with up being positive.
3. **z** is the offset along the beamline (in the direction that the CESR positrons travel). It will be the most poorly determined of the translations, since it is measured only through the ZD stereo angle.
4. **phix** is the angle that the ZD makes with respect to the X axis. If the ZD were an airplane, **phix** would be the pitch. The angles are presented in milliradians. Another way to think of this parameter is that a nonzero **phix** is a +**y** offset on one ZD endcap, and a –**y** offset on the other.
5. **phiy** is the angle that the ZD makes with respect to the Y axis, also in milliradians. It can also be called the yaw, or an antisymmetric offset in **x** on the ZD endcaps.
6. **phiz** is the angle that the ZD makes with respect to the Z axis, or the roll. Unlike the other two angles, this one is in the X-Y plane and is therefore most easily measured.

   In principle, one would need to worry about which order these rotations are applied in the code, since they don't commute. In practice, though, these corrections are small (less than 0.01 radians), so any alignment on a fine enough scale for this to matter would be done with a MINUIT minimization, anyway.

Because suez expresses all lengths and angles in meters and radians while ZDAlignmentMod expresses them in millimeters and milliradians, ZDAlignmentMod always multiplies by a thousand when reading them in from constants and divides by a thousand when writing out to constants or when telling suez what to do with them. This is handled correctly.

The remaining parameters were implemented as experiments, and then never removed. Most of these will not be useful, and you may remove them if you are desperate for screen space.

7. **t0**
8. **drift** If the parameter "fakeDriftFunction" is set to true, ZD drift measurements won't be taken from `distance()`, which includes all calibrations and corrections, but from `time()`, the raw drift time. **t0** and **drift** are the offset and slope of a linear drift function. This may be used as a cross-check if you are afraid that the drift functions are hiding alignment issues.
9. **radius**
10. **del_rad_45** One can artificially change the slope of a residual versus $\cot(\theta)$ plot by adjusting the assumed radius of all wires in the chamber. Don't do this.

    The second parameter, **del_rad_45**, allows you shift the radii of wires in U layers differently from those in V layers. Don't do this either.
11. **sagx**
12. **sagy** These adjust the gravitational sag of wires in the X and Y directions. (It takes some imagination to explain a sag in the X direction, but CESR is built into a hill...) The default sag is zero, as it should be too small to measure in either direction.

13. **twistWest** allows the user to apply a different **phiz** on the west endplate than the east— an *internal* alignment of the ZD. The default value of this parameter is nonzero because the internal alignment has already been fixed.

2.2.4 How to interpret the plots

Only one of the seven plots is a one-dimensional histogram: **resid** plots the number of hits per ZD residual bin. It should be narrow and roughly Gaussian, with an RMS of about 0.1–0.2 mm. For internal consistency, all residuals are reported in millimeters, even in the plots, so the numbers on the horizontal axis are also in millimeters. (This also saves screen space, since 1, 2, 3 takes less room than 0.001, 0.002, 0.003.) In pathological cases, this plot might have a wide, flat-topped peak if the ZD is not properly aligned, two or more peaks if it is way out of alignment, or a long tail if a necessary correction is being ignored, for example.

All of the other plots are profile histograms, and all vertical axes are ZD residuals in millimeters.

- "V ndrift" plots residuals versus normalized drift distance. ("V" always means "ZD residual versus.") The normalized drift distance is the measured drift in units of the cell width. (Bins ± 1 are filled with hits at the edge of the drift cell, 0 with hits very close to the wire, etc.) A **phiz** rotation can vertically raise and lower the entries in this plot, but it is mostly intended to diagnose the problems with T0s (a calibration issue). A gap between positive and negative drift distances indicates a global T0 problem.
- "V layer" plots residuals versus layer number. A gap between layers 2, 3 and layers 4, 5 indicates a **Z** offset, since the first three layers have a different stereo angle from the last three layers.
- "V cotTheta" plots residual versus track $\cot(\theta)$, or, for a given layer, residual along the length of the wire. A track with $\cot(\theta) = 0$ points directly into the barrel, $\cot(\theta) = \pm 1.49$ points into the corner of the barrel region, and $\cot(\theta) = \pm 2$ is the furthest into the endcap that DR Z measurement can be trusted.

  Solving outstanding problems in ZD alignment will probably involve doing something with this plot. There is a slight (100 micron) bowing in *timelike* residuals versus $\cot(\theta)$— this indicates that some ZD hit corrections are not being applied correctly. I don't know why there's a slope in spacelike residuals versus $\cot(\theta)$.
- "V phi (–theta)" plots residual versus ϕ for $-2.0 < \cot(\theta) < -1.4$.
- "V phi (0theta)" plots residual versus ϕ for $-1.4 < \cot(\theta) < +1.4$.
- "V phi (+theta)" plots residual versus ϕ for $+1.4 < \cot(\theta) < +2.0$.

  Sine and cosine curves in all three plots indicate **x** and **y** misalignments. This is the most easily recognized ZD alignment issue. If there is a sine or cosine curve in "–theta", a flat line in "0theta", and a sine or cosine with the opposite sign in "+theta", then **phix** or **phiy** are wrong. Usually, there will be some linear combination of **x**, **y**, **phix**, and **phiy** misalignments— the `mini` command is useful for that.

2.2.5 Crash recovery and results extraction

If suez dies while running ZDAlignmentMod, it won't take your carefully optimized alignment to the grave. Every time FCN is evaluated, ZDAlignmentMod prints the current trial alignment to `state.zdgeomalignment` and `state.pars`— two permanent copies of the most valuable six numbers in memory. `state.pars` has the current ZD alignment (as well as all the other parameters) expressed as a list of MINUIT interactive commands. To recover from a crash at exactly the point where you left off, re-run `suez -f align.tcl`, `iterator go`, and paste the contents of `state.pars` into the terminal.

If suez crashes in the middle of a MINUIT optimization, `state.*` may be filled with a very bad trial alignment. The best alignment (in terms of minimum RMS residual) is printed into `best.zdgeomalignment` and `best.pars`.

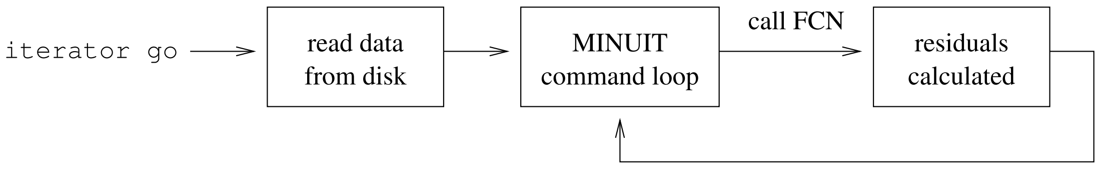
Once you have your final alignment, it has already been printed to `state.zdgeomalignment` and probably `best.zdgeomalignment`, so there is no special way to extract the results. Just kill suez.

2.3 ZDAlignmentMod Implementation

ZDAlignmentMod is an iterator module. If you are familiar with suez, you probably know about processors, which are invoked only when a stop is reached in the data stream, and producers, which are invoked only when data is extracted. An iterator module is given control over the whole processing of the data stream: it *contains* a loop over events. `iterator go` on the suez command line calls ZDAlignmentMod's `iterate()` function, giving it a set of FIFrameIterators to step through Frames. After reaching the last event in the data stream, ZDAlignmentMod is free to change the ZD geometry constants and run over all events again.

While this is, in principle, how an iterator module ought to be written, I wanted to save time by walking through the data stream (on disk) only once. ZDAlignmentMod loads all of the tracks and hits into large STL_VECTORs on the first pass, and then whenever the geometry constants change, it just returns to the first event as a way to get the suez environment to notice the new constants.

A basic sketch of the program flow is as follows:



The ZDAlignmentMod module is built from three classes.

- **ZDAlignmentMod** declares parameters, loads tracks and hits, performs all hit-level cuts except the bad wire cut, and then invokes MINUIT interactive mode.
- The tracks that are loaded from the event stream have only been singly-fit, so **ZDAlignmentDualTrackConstraint** is called to perform the dual-track constraint before storing the dual tracks into memory. (Unlike the dual-track constraint in HelixIntersection, this one implements a full five-parameter fit.)
- Through the magic of MinuitInterface, MINUIT is given **ZDAlignmentFcn** as its FCN. This class actually stores the tracks and hits, opens the HistogramViewer

window, declares histograms, calls ZD geometry objects to calculate residuals, fills those histograms, and writes out `state.*` and `best.*`.

Don't be confused by the fact that **ZDAlignmentMod** and **ZDAlignmentFcn** both have `iterate()` methods. `ZDAlignmentMod::iterate()` is what gets called when you `iterator go`, and `ZDAlignmentFcn::iterate()` is what gets called by MINUIT. They are completely different and have nothing to do with one another.

2.4 A walk through the ZDAlignmentMod code

Before stepping through the code, I want to point out which essential parts of the process are contained in other libraries, in case you're looking for them.

- The algorithm which minimizes the residual RMS when you type `mini`, and the whole command loop itself, is in MINUIT, not ZDAlignmentMod. Perhaps you knew this.
- When ordinary tracks are dual-fit, the application of that constraint happens in HelixIntersection. **ZDAlignmentDualTrackConstraint** only defines equations that would be satisfied by a completely constrained pair of tracks and the derivatives of those equations with respect to track parameters. The application of the constraint happens in **ZDAlignmentDualTrackConstraint**'s superclass when the inherited `applyConstraint()` method is called.
- Whenever constants (like the ZD geometry parameters) are changed, the whole suez world (including AZDSenseWireStore) needs to be made aware of that update, or new calculations of residuals will yield old results. Because the author of the iterator module superclass was expecting an event loop to follow any constants update, suez is only updated when you set a FIFrameIterator using the "=" operator. (As one might at the beginning of a `for` loop over events.)

  But ZDAlignmentMod loops over the data stream only once. After each change to the geometry constants, I create a new FIFrameIterator and set it equal to a FIFrameIterator pointer I have stored for this purpose, like this:

  ```
  FIFrameIterator itFrame = *m_frame;
  ```

  It doesn't matter which event `itFrame` points to, but this line is needed to update the ZD geometry in AZDSenseWireStore.

2.4.1 A walk through `ZDAlignmentMod::iterate()`

When the user types `iterator go` on the suez command line, the function `ZDAlign-`mentMod::iterate(const FIFrameIterator& iBegin, iEnd) is executed. If this is the first time (i.e. the user didn't exit the MINUIT command loop and type `iterator go` a second time), the module will load the two constants files: the ZDGeomAlignment file pointed to by the "geom" parameter and the AZDGeomLayer file pointed to by "geomLayer." `m_geometry` and `m_geomlayer` are CLEOConstantsModifiable objects, and they're connected to the suez world by FIHolders, registered in ZDAlignmentMod's constructor. As soon as `itFrame = *m_frame` is executed, any extraction of ZDGeomAlignment or AZDGeomLayer will get the values in `m_geometry` and `m_geomlayer`.

Also on the first `iterator go`, MINUIT is given parameter values from the ZDGeomAlignment constants. Only the first line (indexed by `[0]` in the code and 1 in the text file) is used because the first line describes bulk alignment. Lines `[1]` and `[2]` (2 and 3) describe internal alignments of the east and west endcaps.

Outside the `m_first_time` conditional, `m_fcn.reset(iBegin)` is called. `m_fcn` is the only instance of **ZDAlignmentFcn**, which is a MinuitInterface MIFcn, loaded into MINUIT in ZDAlignmentMod's constructor. It has two divers functions: it deletes all memory-resident tracks and hits so it will be ready for a new set, and it keeps track of the first Frame pointer, so that **ZDAlignmentFcn** can call `itFrame = *m_frame` all by itself.

Next is the loop over FIFrameIterators; this part looks more like a typical processor. FATables and FAItems are extracted from the Frames, and there are subloops over tracks and hits.

The first thing that happens in this loop is a call to another multifaceted function in **ZDAlignmentFcn**— this one is named `book()` because one of the things it might do is book histograms. The only thing it will always do is notify **ZDAlignmentFcn** of possible new values of the "showPlots" and "fakeDriftFunctions" parameters. Everything else is only done if this is the first call to `book()`:

1. **ZDAlignmentFcn** will read AZDGeomLayer to find the original wire radii. It needs to keep track of them in case the user alters these constants using the parameters **radius** and **del_rad_45**. (E shouldn't.)
2. **ZDAlignmentFcn** will book the seven histograms.
3. **ZDAlignmentFcn** will initialize Qt and the HistogramViewer window. It is at this point in the code that control is given to the user, who needs to open and arrange histogram subwindows, and then press "Continue."

Back in `ZDAlignmentMod::iterate()`, tracks, ZD hits, and the magnetic field are extracted from the Frame (ultimately from the PDS file). ZDAlignmentBhabhaFilterProc should have already filtered out all events with more or less than two tracks in each event, so ZDAlignmentMod assumes there are two. If there are fewer, `++two` will segmentation fault and if there are more, `ZDAlignmentDualTrackConstraint::constraint()` will assert. (There will also be an assertion if the track reference points are at different places. Inward or ChisqFit tracks should always have a reference point of (0, 0, 0).) The two tracks are copied as HIFitHelixes, because this is what HIFitConstraint uses internally.

The dual-track constraint is declared and applied in two lines: the first constructs a temporary **ZDAlignmentDualTrackConstraint** object (this is what MagneticField is needed for), and the second executes the dual-track fit. **ZDAlignmentDualTrackConstraint** defines the constraint as an STL_VECTOR of five constraint equations:

- ${d_0}^{\text{track 1}} + {d_0}^{\text{track 2}} = 0$
- ${z_0}^{\text{track 1}} - {z_0}^{\text{track 2}} = 0$
- • • $\langle p_x, p_y, p_z \rangle = \langle -15\text{MeV}, 0, 0 \rangle$

The right-hand side fo the last constraint is not $\langle 0, 0, 0 \rangle$ because the two incident beams are slightly crossed in the X-Z plane, and 15 MeV is the virtual photon momentum. This number comes from a measurement on $\psi(3770)$ data— if the crossing angle or beam energy changes, this should be reevaluated. (If this value is wrong, you would see a wave in ZDAlignmentBhabhaFilterProc's "tracks momentum phi" histogram.)

These constraints are expressed as a method of **ZDAlignmentDualTrackConstraint**, `constraint()`, which maps track parameters to a vector which is $\langle 0, 0, 0, 0, 0\rangle$ when the constraints are satisfied. Another method, `constraintDerivatives()`, maps track parameters to a matrix of partial derivatives ∂constraint/∂track-parameter for the dual track fitter. Be aware that while STL_VECTORs index with square brackets, starting with zero, HepMatrixes index with parentheses, starting with one. I tried to make the difference in indexing explicit with a `const int offset`.

ZDAlignmentDualTrackConstraint is the only part of ZDAlignmentMod that depends on the magnetic field, and the way it does so is not even strictly necessary. The magnetic field is used to convert track curvatures into momenta. If the constraint merely required the two tracks to have equal and opposite momenta, this factor of magnetic field would be irrelevant— instead of constraining momentum, I could have constrained momentum/magnetic field magnitude. The normalization is only important for comparison with crossing angle, because I expressed it in MeV. There are other ways to express a crossing angle (most of them in radians), but "the momentum of the virtual photon" is the most unambiguous and easiest-to-measure way of describing it that I am aware of, so this is how I coded it. Just be aware that this introduces an implicit dependence on beam energy.

Back in `ZDAlignmentMod::iterate()`, the dual-track constraint has just been applied, and now it is time to drop events if their dual-χ^2 is too high. (High dual-χ^2s are strongly correlated with high $|p_z|$: initial state radiation in one of the incident beams gives the bhabha event a z-boost.) Both dual-constrained tracks are passed through a tighter cut on $\cot(\theta)$. (Yes, the one on the second track is redundant.)

Next is a loop over the two tracks, and within that, a loop over all ZD hits on those tracks. Temporary vectors of hits and signed drift distances are filled if the hits pass `kFITTABLE`, drift distance, and layer-number cuts. If, after these cuts, a track has any ZD hits left, the track, hits, signed drift distances, and the average (ZD) charge on the track are passed to **ZDAlignmentFcn**, so that it can insert these data into its vectors.

ZDAlignmentFcn fills its vectors with a terrifying `fill()` method. Instead of creating structures, I just made sure that vectors containing information for the same event had the same indices. There is one average charge per track, but possibly more than one hit and signed drift distance, so the latter need to be declared as vectors of vectors. Moreover, to avoid impicit calling of vector and `CalibratedZDHit` constructors, the elements of these nested vectors need to be pointers to vectors and hit objects, rather than the objects themselves. Consequently, `fill()` is rife with referencing and dereferencing. A lot of this structure could have been hidden with type declarations, but I think it is clearer to include all the asterisks.

`ZDAlignmentMod::iterate()` ends with a call to MINUIT— usually a call to enter the command loop (`m_minuit->interact()`)— but if the parameter "interactive" is false, MINUIT goes right into minimization (`m_minuit->runMigrad()`). In either case, MINUIT takes over, and ZDAlignmentMod is only ever given control again when `ZDAlignmentFcn::iterate()`, the suez implementation of FCN, is called. If the user types "show par", this happens right away.

2.4.2 A walk through `ZDAlignmentFcn::iterate()`

When MINUIT calls FCN, the function `ZDAlignmentFcn::iterate(double* v)` is executed. The array `v` holds the thirteen current trial parameter values. **ZDAlignmentFcn** immediately sets the CLEOConstantsModifiable objects to these values and prints them out to `state.zdgeomalignment` and `state.pars`. Then

$$\text{FIFrameIterator itFrame} = {}^{*}\text{m\_frame};$$

is executed, and suez is notified of the changes. The ZD hit corrector, AZDSenseWireStore, and ZD gas description are re-extracted from the Frame (which points uselessly at the first event). I only expect AZDSenseWireStore to differ with each change to the geometry constants.

Next, the histograms are reset. If this segmentation faults, or if histograms are not being reset properly, you probably need to get a post-Oct15_03_MC change to HbookHistogram which corrects a bug in `reset()`.

Next comes a nested loop over tracks and hits. In the track loop, four vectors need to be iterated-over simultaneously: `m_track`, `m_charge`, `m_vect`, and `m_drifts`. A `while` loop checks for the end of the `m_track` vector, and immediately asserts if the other three haven't reached their ends. All four iterators are incremented at the end of the `while` loop. Two of these, `m_vect` and `m_drifts`, are vectors of vectors: iteration over the second level in this hierarchy is the hit loop. This loop is implemented the same way: a `while` with an assertion at the beginning and incrementation at the end. If you're adding structure, like another variable to be stored alongside tracks or hits, be very careful to include all the necessary parts— a missing incrementor would be a silent bug. (New variables must be correctly deleted in `reset()`, inserted in `fill()`, have iterators initialized before the `while` loop, assertions at the beginning of the `while` block, and incrementors at the end of the `while` block.)

Bad wires are cut at the beginning of the hit loop, though they might as well be dropped in `ZDAlignmentMod::iterate()` with the other hit-level cuts. (Then they wouldn't even be loaded into memory, which would be a good thing.)

Next, **ZDAlignmentFcn** projects its local copy of the track helix to a single ZD hit. The standard routines for doing this were written for track fitters; our job is much simpler, but we can re-use many of the same routines.

	A normal track fitter	**ZDAlignmentFcn**
1.	Create a HIZDSurfaceFactory and apply it to the current event. (This requires the tracks to have come from the Frame.)	Create a vector of HIIntersectionSurfaces and fill it with one HISingleWireCylinder pointer.
2.	Create a HIHelixIntersector, feed it the surfaces, and tell it to sort them in increasing radius.	Create a HIHelixIntersector, feed it the surfaces (one surface), and tell it to not bother sorting.
3.	Use `swimToCurrentSurface()` to loop over surfaces, and process the hit at each stop. The helix's reference point is implicitly moved to the point of closest approach to each hit.	Explicitly move the track's reference point close to the hit so that swimming is a smaller extrapolation. Call `swimToCurrentSurface()` once.

4.	At each hit, execute `applyTrackCorrections()` to apply corrections to the hit which require knowledge of the track.	Execute `applyTrackCorrections()` to apply corrections to the hit which require knowledge of the track.

This is where signed drift distances and average track charges are needed: they are given to HISingleWireCylinder's constructor. (Kalman and ChisqFitter keep track of this extra information with a `HIZDSurfaceFactory::ZDHitAndDriftDistance` list.) These signed drift distances carry one more bit of information than the `distance()` you can get from CalibratedZDHit: the sign they are given comes from a collection of algorithms in DoitProd which use neighboring hits to determine which side of the wire a given drift measurement came from. This sign assignment is far more accurate than assuming the drift measurement is from the same side as the projected distance of closest approach. I don't know what is done with the average track charges, and I don't know if averaging over the charges of only ZD hits is sufficient.

Once the track has been swum and track-dependent hit corrections applied, many variables are extracted from the intersector, surface, hit, and swum helix, and these are used to fill the histograms. It is entirely likely that new histograms will be needed in the future; this is where their contents will be calculated. If the user turns on the "fakeDriftFunctions" parameter, this is where the carefully calculated signed drift distance is tossed in favor of a linear extrapolation. This could easily be modified to inherit the sign from the track finder.

Lastly, the HISingleWireCylinder created with a `new` operator must be deleted before the end of the hit loop, to prevent a massive memory leak.

After the track and hit loops, the histograms have all been refilled, so it is time to draw them on the screen. (This execution of the Qt application gives the user zero milliseconds to move any subwindows around— if it did wait for the user, minimizations would take longer than they would have to.)

The root-mean-square residual is calculated, and, if it is better than any **ZDAlignmentFcn** has seen so far, **ZDAlignmentFcn** will print all the pertinent parameters to `best.zdgeomalignment` and `best.pars`. This RMS is then returned to MINUIT, and MINUIT may decide to sample another set of parameters and try again.

3 DRAlignmentMod (and DRAlignmentBhabhaFilterProc)

3.1 Differences in DRAlignmentMod Strategy

Until now, we have been discussing the problem of how to find the correct alignment of a solid object— the ZD— from residuals of hits to tracks fitted in the DR. DR alignment presents a slightly different problem: the wedding cake, the part of the DR that needs to be aligned, is made of eight distinct cake rings with two endplates each, and all sixteen parts can move independently. Fortunately, because a DR wedding cake endplate only determines hit positions in the X-Y plane, **z** is neither measureable nor relevant. Additionally, **phix** and **phiy** would only make small changes to 2-D hit positions, so only three parameters are left per endplate. If tracks are fit only to the DR stereo section, residuals in one cake ring are completely independent of the alignment of any other cake ring, so the problem splits up into eight independent ones, with only six parameters each.

ZD Alignment	**DR Alignment**
1 solid object	16 solid objects
1 alignment process	reducible to 8 independent alignments
6 parameters	3 parameters × 2 objects per alignment

DR alignment has a different set of six parameters, and acts on only one cake ring.

1. **xEast** is the offset of an east cake ring, in the direction along the floor and perpendicular to the beam axis.
2. **yEast** is the vertical offset of an east cake ring
3. **phiEast** is the distance the outer radius of an east cake ring is rotated around the beamline
4. **xWest** is the x offset of a west cake ring (west is the direction of incident positrons)
5. **yWest** is the y offset of a west cake ring
6. **phiWest** is the distance of a west cake ring rotation

Beyond that, the procedure is remarkably similar. Therefore, I made a tool for DR alignment by copying ZDAlignmentMod and changing all instances of "ZD" to "DR." This may sound like a horrible cheat, but it makes it easier for a new person to take over the project, since the code is nearly the same. Differences will evolve over time, so someday knowledge of ZDAlignmentMod won't help someone understand DRAlignmentMod, but I should hope alignment is a solved problem by then!

A good introduction to DRAlignmentMod strategy is therefore Section 2.1, ZDAlignmentMod Strategy (page 3). The discussion of residuals, drifts and dcas still apply because the DR is as much a wire chamber as the ZD. DRAlignmentMod loads tracks and hits from a pre-filtered source (DRAlignmentBhabhaFilterProc) the same way and calls MINUIT for its command loop. DRAlignmentMod uses the same dual-track constraint, though it defines its own constraint class, **DRAlignmentDualTrackConstraint** (which is exactly the same). It is still wise to use ChisqFitProd as a fitter, and the event selections defined in DRAlignmentBhabhaFilterProc and DRAlignmentMod are the same as in the ZDAlignment counterparts (except the requirement for tracks with at least one ZD hit— in the DR version, at least eight axial DR hits are required). By default, only time-of-flight and signal-propogation corrections are applied to DR hits. This is the right thing for ZD hits, but perhaps the DR is understood well enough that more track-dependent corrections may be applied.

Most ZD hit selections have no analogue for the DR, so the only DR hit selection that is applied is the drift distance cut: only DR hits between 1.5 and 3.8 mm are passed.

The last issue is one of numerology: the axial section is composed of eight wedding cake rings (the physical structure) and sixteen layers (the sense wires). Each cake ring has two sense wires— two layers. Cake rings and layers are both numbered in increasing radius: cake ring 1 is closest to the beampipe and suspends sense wires in layers 1 and 2. DRAlignmentMod has two `const` functions for converting from layers to cake rings: `DRAlignmentMod::cake_ring()` and `DRAlignmentFcn::cake_ring()`.

3.2 Differences in DRAlignmentMod Use

3.2.1 Differences in running DRAlignmentBhabhaFilterProc

Just like ZDAlignmentMod, DRAlignmentMod expects tracks and hits to come pre-reconstructed and pre-selected from a PDS file. The event filter for DR alignment is DRAlignmentBhabhaFilterProc, and, as stated above, almost all the same cuts are applied.

Because we are now aligning the DR axial section, it is now necessary to fit the tracks to the stereo section only, rather than the whole DR. (We should still leave the ZD out of the fit!) It is a bit more difficult to deweight part of a detector— the DR axial section— rather than a whole detector. An example of how to do this is illustrated by DRAlignmentBhabhaFilterProc/Test/sample.tcl and DRAlignmentBhabhaFilterProc/Test/deweight_axial.drweight2layerdriftentang. If the fittingweights change, you will need to create a new deweighted deweighted_axial file from the new fittingweights. Here's how to do it:

1. Make a local copy of the latest DR fittingweights (bdl type DRWeight2LayerDriftEntAng). If these weights are in the database, you can use the constants website (page 7). (Wherever you get them from, be sure to set the first two numbers to "1 0" so the file will be used for any run range.)
2. Edit your local copy so that any line with a layer number (first column) from 1 to 16 has a very large fittingweight (last column). 1000 will do. (Why a large number, rather than a small one? See page 6 for an explaination.) An awk commandline that will do this is:

   ```
   awk '(  $1>0 && $1<17 && $9!="DEFAULT" ){print $1 $2 $3 1000}
        (!($1>0 && $1<17 && $9!="DEFAULT")){print $0}
        < in.drweight2layerdriftentang > out.drweight2layerdriftentang
   ```
3. Load this as the new fittingweights:

   ```
   source_format sel DRWeight2LayerDriftEntAngFileSourceFormat
   file in out.drweight2layerdriftentang
   ```

In direct analogy to ZDAlignmentMod, DRAlignmentMod needs the following data to run:

- FAItem<DBEventHeader>
- FAItem<DBTrackerValues>
- FATable<TRTrack>
- FATable<TRHelixPionFit>
- FAItem<SeedTrackDRHitLattice>
- FATable<CalibratedDRHit>

3.2.2 Differences in running DRAlignmentMod

Like ZDAlignmentMod, DRAlignmentMod will require a starting geometry— bdl type DRGeomAlignment— which you can get from the same website (page 7). Be sure to set the first two numbers to "1 0" so the file will be used for any run range. Point

DRAlignmentMod to that file with "geom" in the same way. DRAlignmentMod doesn't provide any naughty parameters that shift wire position radius or wire sag, so no ADRGeomLayer is needed.

Even though they look superficially similar, the DRGeomAlignment constants are interpreted very differently from their ZD counterparts.

ZDGeomAlignment indices		DRGeomAlignment indices	
		1	DR bulk alignment
		2	East stereo endplate
1	Bulk alignment	3 ⋮ 10	East cake rings 1–8
2	East endcap alignment		
3	West endcap alignment	11 ⋮ 18	West cake rings 1–8

Also, while ZDGeomAlignment is in normal CLEO-III units (meters and radians), DRGeomAlignment is completely in inches. The three angles, **phix**, **phiy**, and **phiz** are in inches at the outer radius of the cake ring. Internally, DRAlignmentMod uses only millimeters, and it does all the conversions from constants/files to MINUIT and back to constants/files correctly. There are two problems with this situation: everything the user sees in MINUIT is an awkward factor of 25.4 different from what e sees in the constants files, and the angles are still in a wierd unit: millimeters at the outer radius.

When you run the corresponding `align.tcl`, be aware that it sets a new parameter called "ring." This specifies which cake ring number you will be aligning. One way to align all eight is to start with "ring" set to 1, enter the MINUIT command loop with `iterator go`, do an alignment, exit MINUIT with `exit` (don't `exit` twice!), set the "ring" parameter to 2, enter MINUIT again, etc. `state.*` and `best.*` will include cumulative changes. If you encounter a crash partway through, load `state.drgeomalignment` or `best.drgeomalignment` with "geom" to return to your last or best alignment.

But perhaps you don't have this kind of patience— suppose you want to log into eight machines at the same time, align a different cake ring in each, and then collect results. This can be done in principle because calculations of residuals of one cake ring are independent of the alignment of other cake rings. But all of your jobs would be printing their latest and best states to the same files— you would need to edit `DRAlignmentFcn::iterate()` (near lines 266 and 398 of DRAlignmentFcn.cc) to print out different file names depending on the value of `int m_ring`. You would then have to merge the outputs of the eight files.

Like ZDAlignmentMod, DRAlignmentMod has two extra parameters for faking drift functions with a straight line:

7. **t0** — offset time
8. **drift** — drift velocity

but it doesn't have all the others. This is because I don't expect the others to be useful, so I didn't want to port them to a DR-alignment context.

DRAlignmentMod has one fewer histogram than ZDAlignmentMod: "V layer" (residual versus layer) is not useful for DR alignment because it measures a difference between U layers and V layers; the axial section of the DR has neither. All the other histograms are the same. Even the three "V phi" histograms have the same $\cot(\theta)$ cuts as their ZD counterparts, but they are labelled "east," "mid," and "west" to help you determine whether you should shift the east endplate or the west endplate to cancel a distortion.

These are all the differences between DR and ZD alignment tools as of January 23, 2004. Others are bound to appear as DRAlignmentMod becomes better specialized to its unique task. Be sure to check the CVS log for names other than mine!

4 DualTrackProd (and DualTrackToUsageTagProd)

One part of ZD- and DRAlignmentMod is a new dual-track constraint (described in Section 2.1.1 on page 3). This constraint differs from the one used in silicon alignment in that it is a five parameter constraint (the old one didn't constrain p_z), crossing angle is now expressed as a momentum shift, and perhaps most importantly, hit residuals are calculated with the new dual-tracks. When it became clear that this new constraint would be useful in other alignment and calibration work, I wrapped it in a producer so that it is easily accessible in suez.

A number of technical issues made it easier to replace the existing structure than to modify it, although this raises the possibility of name confusion. These are the old and new names (middle and right, respectively):

HIFitConstraint subclass	HelixIntersection/HIDual-TrackConstraint	DualTrackProd/DualTrack-Constraint
Extractable object	DualTrackHelices/Dual-TrackHelices (FATable)	DualTrackProd/DualTrack (FAItem)
Producer	DualTrackHelicesProd	DualTrackProd
Conversion to standard helix and lattice objects		DualTrackToUsageTagProd

The constraint in DualTrackProd is a cut-and-paste copy of the one in ZDAlignmentMod. While ZDAlignmentMod and DRAlignmentMod are both sinlge-use tools, and therefore meant to be very open to modification and replaced when they become too hairy to work with, DualTrackProd is a finished product— we should think of the code in DualTrackProd as the original and the alignment modules as containing temporary copies. The best thing would be to rewrite the AlignmentMods to extract dual-track objects from DualTrackProd, rather than defining their own, but I haven't done this because they are just temporary, after all.

4.1 How to Use DualTrackProd

Before describing the various methods of extracting dual-tracks, I want to warn you that the specification of the crossing angle depends on beam energy. The default crossing angle DualTrackProd uses is 15 MeV in the $-\hat{x}$ direction, which comes from a measurement at $\psi(3770)$. If your bhabhas are above 4270 or below 3270 MeV, it would be wise to re-measure the crossing angle with the "printOutP" parameter described on page 24.

4.1.1 Extracting via special DualTrack types

If you are building a new processor/producer, here's the simplest way to get dual-tracks:

1. Load DualTrackProd in your tcl script with `prod sel DualTrackProd`.
2. Include `"DualTrackProd/DualTrack.h"` in your `.h` or `.cc`.
3. Extract a DualTrack object from the event stream:

```
FAItem<DualTrack> dual_track;
extract(iFrame.record(Stream::kEvent), dual_track);
```

- If this event successfully performed a dual-track fit, `dual_track->results().fit-Successful()` will be true. (You don't need to pre-select two-track events—unsuitable events will just have a false `fitSuccessful()` flag.)
- If `dual_track->results().fitSuccessful()` is true, two methods will return DualTrackFitHelix objects: `dual_track->positive()` and `->negative()`. These two objects are tracks (DualTrackFitHelix son of HIFitHelix son of HIHelix is a son of KTHelix), so you can ask for things like `positive().cotTheta()`.
- The quality of the dual-fit can also be found by `results().chisq()` divided by `results().ndof()`.

If you'd rather loop over tracks, you can extract a table of DualTrackFitHelixes.

3.
```
FATable<DualTrackFitHelix> dual_tracks;
extract(iFrame.record(Stream::kEvent), dual_tracks);
for (FATable<DualTrackFitHelix>::const_iterator dualItr =
         dual_tracks.begin();
     dualItr != dual_tracks.end();
     ++dualItr) {
          ⋱
```

These two helices are the same as `dual_track->positive()` and `->negative()`. Incidentally, these have the same `identifier()`s as the singly-fit tracks they correspond to, so you can do things like `navtracks.find(dualItr.identifier())`.

DualTrackProd will also calculate residuals of hits with respect to the dual-constrained tracks.

4. Extract the appropriate lattice (DR or ZD):

```
FAItem<DualTrackZDHitLattice> dual_zdlattice;
extract(iFrame.record(Stream::kEvent), dual_zdlattice);
```

5. Following the existing convention, tracks are on the left of the lattice, and hits are on the right.

```
    // (in DualTrackFitHelix loop)
    const DualTrackZDHitLattice::Links& dual_zdlinks =
      dual_zdlattice->linksGivenLeft(dualItr->identifier());
```

```
DualTrackZDHitLattice::Links::const_iterator dual_zdlinkItr =
  dual_zdlinks.begin();
DualTrackZDHitLattice::Links::const_iterator dual_zdlinkEnd =
  dual_zdlinks.end();
for (; dual_zdlinkItr != dual_zdlinkEnd;  ++dual_zdlinkItr) {
    const CalibratedZDHit::Identifier* hitId =
      (**dual_zdlinkItr).rightID();
    DualTrackZDHitLink& linkData = (**dual_zdlinkItr).linkData();
    linkData.residual();
```

4.1.2 Extracting via a usage tag

If you have an existing processor/producer which already loads singly-fit tracks and residuals and want to modify it to load dual-constrained tracks and residuals instead, the above procedure would be inconvenient because you would need to change all the type names. Here's an alternative way to get dual-tracks and -hits, which will be easier to merge:

1. Load these two producers in your tcl script:

   ```
   prod sel DualTrackProd
   prod sel DualTrackToUsageTagProd
   ```

2. No DualTrack include files are needed.

3. Change TRHelixFit and FitDRHitLattice extractions to request the "DualTrack" usage tag. The extract lines of

   ```
   FATable<TRHelixElectronFit> tracks;
   FAItem<ElectronFitDRHitLattice> drlattice;
   FAItem<ElectronFitZDHitLattice> zdlattice;
   extract(iFrame.record(Stream::kEvent), tracks);
   extract(iFrame.record(Stream::kEvent), drlattice);
   extract(iFrame.record(Stream::kEvent), zdlattice);
   ```

   become

   ```
   extract(iFrame.record(Stream::kEvent), tracks, "DualTrack");
   extract(iFrame.record(Stream::kEvent), drlattice, "DualTrack");
   extract(iFrame.record(Stream::kEvent), zdlattice, "DualTrack");
   ```

   It doesn't matter which mass hypothesis you extract— the dual-track constraint is applied to one hypothesis and DualTrackToUsageTagProd fills all hypotheses with the same modified track.

You can still extract a DualTrack object directly to get information about the dual-χ^2.

4.1.3 Extracting via NavTrack with a production tag

The situation becomes a bit more complicated if you're getting your tracks and hits from NavTrack, because DualTrackProd gets its singly-fit tracks from NavTrack. But there's a way to do this, too: you just need to load two instances of NavigationProd.

Here's how to do that:

1. Load all of the following into your tcl script.

   ```
   # This NavigationProd holds singly-fit tracks
   prod sel NavigationProd
   prod sel TrackDelivery

   prod sel DualTrackProd
   prod sel DualTrackToUsageTagProd

   # Load a second NavigationProd to hold dual-fit tracks
   prod sel NavigationProd production "DualTrack"
   prod sel TrackDeliveryProd production "DualTrack"
   param NavigationProd@DualTrack fitterUsageTag "DualTrack"
   param TrackDeliveryProd@DualTrack fitterUsageTag "DualTrack"
   ```

2. No DualTrack include files are needed.

3. Now, instead of requesting a special usage tag, we extract a special production tag.

   ```
   FATable<NavTrack> navtracks;
   extract(iFrame.record(Stream::kEvent), navtracks);
   ```

   becomes

   ```
   FATable<NavTrack> dual_navtracks;
   extract(iFrame.record(Stream::kEvent),
                                    dual_navtracks, "", "DualTrack");
   ```

   (In fact, you can extract both.)

- Now you should be able to use the NavTrack conveniences.

  ```
  FATable<NavTrack>::const_iterator dual_navtrackItr =
      dual_navtracks.begin();
  const FATable<NavTrack>::ZDHitLinkTable* dual_zdlinks =
      dual_navtrackItr->pionZDLinks();
  ```

4.2 Everything you want to know about DualTrackProd

4.2.1 DualTrackProd parameters

Descriptions of the DualTrackProd parameters are also available through the normal suez parameter help system.

- "massHypo" allows you to pick which mass hypothesis to dual-constrain. It is a string, and its value must be one of "electron," "muon," "pion," "kaon," "proton," "exitElectron," "exitMuon," "exitPion," "exitKaon," and "exitProton."

- “vphoPx”
- “vphoPy”
- “vphoPz” allows you to set the 3-momentum of the virtual photon before it decays into back-to-back particles. “Px” and “Py” physically correspond to a crossing angle of the incident beams, which is by default $\langle$ 15 MeV, 0 $\rangle$. A non-zero “Pz” would arise from asymmetric beams, which are not available at CESR.

  Be careful of the sign convention here: it’s wrong. Considering that I’m calling this “the virtual photon momentum” rather than “the virtual photon coordinate frame boost,” it goes the wrong way. I would fix it now, but people are already using it, so just print out the default value of “vphoPx” before changing it: that will tell you which way it goes.
- “constrainPoint”
- “constrainPT”
- “constrainPZ” are three options, true by default, which let you set the kind of constraint you want. “constrainPoint” will force the impact parameters d_0 and z_0 of the two tracks to be the same, “constrainPT” will force the total transverse momentum to be consistent with 2D back-to-backness and the crossing angle, and “constrainPZ” will force the total longitudinal momentum to be zero.
- “printOutP” is a diagnostic option. If you set this to true, DualTrackProd will print out the virtual photon 3-momentum for every two-track event, by adding the momenta of singly-fit tracks. You can then put these into an ntuple or histogram to look for the peak in X-Y-Z (or eyeball it if you’re brave). If you are re-measuring the crossing angle because the beam energy has changed, ignore Y and Z.

4.2.2 DualTrack member data

These are all the public member functions of the DualTrack object.

- `const DualTrackFitHelix& positive()`
- `const DualTrackFitHelix& negative()` return track helices for the positive and negative tracks used in the dual-constraint. DualTrackFitHelix is a HIFitHelix, which is a HIHelix, which is a KTHelix.
- `const DualTrackConstraint& constraint()` returns the constraint object itself, which can be useful if you want to calculate the constraint values and derivatives yourself. Be careful: the meanings of the output vector and matrix indices depend on the parameters “constrainPoint,” “constrainPT,” and “constrainPZ.”
- `const HIFitConstraint::Results& results()` returns a results object. A results object has these useful members (and more!):
  - `fitSuccessful()`
  - `deltaTrackParameters()`
  - `chisq()` is the dual-χ^2.
  - `ndof()` depends on the parameters “constrainPoint,” “constrainPT,” and “constrainPZ,” but doesn’t vary from event to event.
- `const HepVector3D& pVirtualPhoton()`

- `DABoolean pointConstraint()`
- `DABoolean ptConstraint()`
- `DABoolean pzConstraint()` tell you the parameter values under which DualTrackProd is being run.

4.2.3 DualTrackZDHitLink and DualTrackDRHitLink member data

- `used()` is the same as the single-fit version (set by the fitter).
- `residual()` is the measured drift − dual-track predicted dca.
- `residualError()` is the error in the measured drift only— no contribution from `signedDcaError()`. This is what ChisqFitProd outputs, so I'm doing the same thing.
- `momentum()` comes entirely from the curvature of the dual-track. Because DualTrackProd doesn't know about dE/dx, this momentum is the same all along the track.
- `trackRefPt()` is the point of closest approach of the dual-track to a given hit.
- `signedDcaToWire()` is the distance of closest approach, predicted by the dual-track.
- `signedDcaError()` is the uncertainty in the above.
- `sinTrackToRadial()` is an approximation of the entrance angle using the dual-track.
- `driftTime()` is the measured time— exactly the same as the single-fit version.
- `fittingWeight()` is the fittingweight assumed in the fit— exactly the same as the single-fit version.
- `signedDriftDistance()` is the measured drift distance— exactly the same as the single-fit version.
- `singleTrack_residual()`
- `singleTrack_residualError()`
- `singleTrack_momentum()`
- `singleTrack_trackRefPt()`
- `singleTrack_signedDcaToWire()`
- `singleTrack_signedDcaError()`
- `singleTrack_sinTrackToRadial()` all provide the user with access to what the singly-fit track determined for this hit. It's just a convenience.

Happy calibrating!