Coordinate frames for offline reconstruction

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Draft 0.3 (11/12/06)

1 Introduction

This note discusses how the coordinate systems / reference frames used in reconstruction should evolve to handle the realistic geometry now being simulated for the calibration / alignment challenge in the CSC production. It builds on the extensive discussion found in [1], although some of the assumptions made at that time have now evolved, as discussed below.

Several objects/concepts are candidates to define a coordinate reference frame, and need to be related to each other:

- The 'global frame', corresponding to the frame in which the positions of ATLAS subdetectors are known before data-taking. Following [1], this frame is denoted GLOB. It is equivalent to the frame sometimes denoted SURV, the frame in which the initial detector position surveys are done.
- Magnetic field frame, denoted SOL. The magnetic field has an approximate axis of symmetry, corresponding (at least approximately) to the direction of the solenoid field. This frame is 'special', in that track trajectories form helices with their axis orientated along this direction (at least in the central solenoid region with constant magnetic field).
- The frame of the beamline, where the colliding protons travel along the z-axis (denoted BEAM). In the approximation that there is no crossing angle, this is equivalent to the physics frame in which there is no p_T in the collision. With a crossing angle, the beamline frame corresponds to the 'average' direction of the two beams, and is also boosted in the transverse plane.

Both the relationships between these frames, and our knowledge of them, may evolve with time (e.g. the direction of the magnetic field may be more precisely known after initial data analysis, and the beamline position will move with time).

2 Choice of coordinate frames

In principle, the choice of coordinate frames is arbitrary, as quantities expressed in one frame can always be transformed into another. In practice however, a bad choice of reference frames can lead to significant extra complication and CPU consumption in the software, together with increased confusion and possibility for errors.

After discussion with experts in the various subsystems, the following concrete choices are proposed:

- **Simulation** will be done in the GLOB frame. Hence this is also the frame in which GeoModel reports the position of modules, and the frame in which the Geant4 geometry is built. This also implies that detector alignment constants will finally relate module positions to the GLOB frame (though local module frames may also be used in building up the GeoModel tree). In general the magnetic field will not be symmetric around the z-axis of the GLOB frame, and will have small B_r and B_ϕ components, even at the centre of the solenoid. The magnetic field service interface will therefore have to return the field in the GLOB frame, typically by using an internal symmetric field map (in the SOL frame), and rotating/translating it into the GLOB frame.
- **Reconstruction** will also be done in the GLOB frame. This is a change from some previous discussions, where local coordinate frames were considered for subdetector reconstruction, perhaps being different from GLOB. In particular, the possibility of doing the ID reconstruction in the SOL frame was considered, to exploit the fact that tracks would be approximate helices around the SOL z-axis. However, the expected deviations of SOL from GLOB are now known to be sufficiently small (O(1 mrad) or

less), that this is not required. Some initial pattern recognition and trigger tracking will be done with the incorrect assumption of GLOB z-axis symmetry, but this will not introduce significant errors, and final offline trackfitting will always be done in GLOB. This makes the subsequent combined reconstruction easier and avoids confusion between conventions in simulation and reconstruction.

- **Physics analysis** *may* be done in the BEAM frame, i.e. the centre-of-mass frame of the collision, with $p_T=0$. This implies small rotations and boosts of the 4-vectors of reconstructed objects away from the values reconstructed in the GLOB frame. It also implies translating any spatial position quantities (e.g. vertex positions) to correct for the beamspot offset, if they are required in this frame. However, it is expected that most use of vertices will occur at the reconstruction or vertex tagging stages, done in the GLOB frame, and the use of spatial positions in the BEAM frame will be rare. The translation between GLOB and BEAM frames will be time-dependent, and will depend on knowledge of the beam tilts, crossing angle and beamspot position. This will come both from reconstruction of physics events and from external constraints (e.g. the crossing angle will have to be supplied by the LHC machine). Whether or not this use of the BEAM frame for analysis is actually desirable is discussed further in Section 5.

The next two sections examine how these choices will work in practice, illustrating with examples from the calibration / alignment challenge (CDC) and real data-taking.

3 Coordinate frames for reconstruction in the CDC

The calibration/alignment challenge has begun by simulating data with a realistic misaligned detector, and with the magnetic field with its axis of symmetry rotated away from the GLOB frame by a transformation $\mathbf{S_0}$. This corresponds to the situation in Figure 1 (left), and the geometry tag ATLAS-CSC-01-02-00. The magnetic field at any point $\mathbf{x}$ in the global frame is actually calculated as $\mathbf{B_{sim}}=\mathbf{B_0}(\mathbf{S_0 x})$, where $\mathbf{B_0}(\mathbf{x})$ is a function giving the symmetric magnetic field configuration. The figure also shows a beamline with a small tilt and crossing angle. However, in the default CSC simulation to date, the beamline has not been displaced from its nominal orientation along the global z-axis, so the beamline transformation $\mathbf{L}$ is unity.

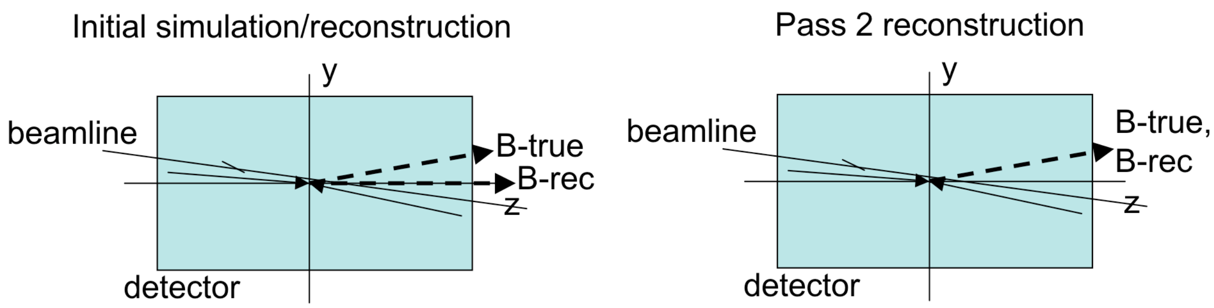

Figure 1: coordinates in the GLOB reference frame for simulation/initial reconstruction (left) and subsequent reconstruction (right). The beamline is shown with a small crossing angle.

Reconstruction is beginning using tag ATLAS-CSC-01-00-00, which uses a non-rotated magnetic field, i.e. $\mathbf{B_{rec}}=\mathbf{B_0}(\mathbf{x})$. The reconstruction reference frame is again the global frame, and the orientation of the various elements corresponds to Figure 1 (left). From this initial reconstruction, several tasks must be performed, in order to produce a set of calibration and alignment constants to be used for the next reconstruction pass. These are discussed in more detail below.

3.1 Inner detector internal alignment

The inner detector will be aligned internally using tracks, starting from the initial nominal positions expressed in the GLOB frame. This process may involve both separate silicon (SCT and pixel) and TRT alignment, and combined alignment, but the end result should be an inner detector which is aligned internally in a self consistent way, with aligned module positions finally expressed by GeoModel in the GLOB frame, and trackfitting also being done in the GLOB frame.

3.2 Muon spectrometer internal alignment

Similarly, the muon spectrometer will be internally aligned using tracks and a simulation of the dedicated muon alignment system, without using the inner detector information. Muon chamber and hit positions will be expressed in the GLOB frame. Note that at present, a rather simple hierarchy of alignable transforms is used for the muon chambers, with a single transform relating the position of each chamber to its position in the overall muon mother volume (TreeTop in GeoModel terminology). This may be replaced in the future with transforms giving its position in the barrel sector (related to each BT coil) or endcap wheel, which is in turn positioned in the overall ATLAS volume. However, this does not change the fact that the end result of all these transforms combined is a chamber position expressed in the GLOB frame.

3.3 ID-muon combined alignment

After the individual alignments of the ID and muon spectrometer, there will still be global shifts and rotations of each part of the muon spectrometer (barrel sectors, endcaps) with respect to the ID. This will be visible in e.g. $\Delta\phi=\phi_{muon}- \phi_{track}$ and similar $\Delta\eta$ distributions. To remove these, each part of the muon spectrometer will have to be globally shifted and rotated in the GLOB frame, either by applying the necessary transformation to each muon chamber's individual alighment constants, or by utilising transformations higher up in the muon spectrometer hierarchy (if implemented). In either case, the net result will be that in the next reconstruction pass, standalone muon tracks will be translated and rotated to better match with tracks reconstructed in the ID, and the $\Delta\phi$ and $\Delta\eta$ should be centred much closer to zero.

The choice of moving the muon chambers and fixing the ID is motivated by two reasons:

- The individual parts of the muon system are only weakly coupled to each other internally, and the strongest constraints may come from the connection through the internally aligned ID. The muon spectrometer parts would in any case have to be moved with respect to each other once the ID information is included.
- The ID is closest to the 'anchor' point of the beamline – globally shifting and rotating the ID would also mean the beamline position/orientation in the GLOB frame would also change.

With this model, ID-muon track matching will not work correctly until the $\Delta\eta$ and $\Delta\phi$ offsets have been dealt with by realigning the muon chambers in the next reconstruction pass. Especially in the early stages of ATLAS datataking, it may be sensible to allow the insertion of explicit corrections to $\Delta\eta$ and $\Delta\phi$ when doing track matching, to put in 'by hand' the corrections which will be made automatically on the next full reconstruction pass. This would allow e.g. muon-track matching of the type presently performed by STACO to be re-done from the AOD data, without the need to wait for full re-reconstruction. However, this type of simple correction will not be possible for combined ID-muon track fitting (treating all the hits in a single track fit), which really needs a consistent alignment of all detector elements on the track.

3.4 ID-calorimeter alignment

Each part of the calorimeter (LAr EM barrel ±z parts, LAr endcap cryostats, tile barrel and extended barrel) is individually placed within ATLAS and will have its own small translation and rotation wrt the GLOB frame. Although the hardware (η,ϕ) segmentation of each calorimeter part naturally defines a 'local' coordinate system and symmetry, this is already broken by calorimeter mechanical imperfections such as the 'pear-shape' caused by it sagging under its own weight. In the present software, such internal misalignment is already taken into account when calculating the (η,ϕ) positions of cells and clusters.

The position of each calorimeter part in the GLOB frame will be derived by studying distributions of $\Delta\phi=\phi_{calo}-\phi_{track}$ and similarly for $\Delta\eta$. As for the muon spectrometer, this information will be used to update the information to calculate the (η,ϕ) positions of calorimeter cells and clusters, so that their position in the GLOB frame changes in the next reconstruction pass, and the $\Delta\phi$ and $\Delta\eta$ distributions move towards being centred on zero. Similarly, hooks for 'temporary' corrections could be provided in TrkToCalo-type tools, to allow track-calorimeter matching to be performed on the AOD, before the next full reconstruction pass.

3.5 Magnetic field alignment

Information on the orientation of the magnetic field relative to the GLOB frame could come from tracks, which would appear to deviate from their expected helical trajectory along the assumed z-axis of the magnetic field. How well this can actually be done should be studied as part of thc calibration and alignment challenge exercises. After this analysis, it will be deduced that the magnetic field is actually rotated with respect to the GLOB frame, by a transformation $\mathbf{S_1}$ (hopefully $\mathbf{S_1} \approx \mathbf{S_0}$). In the next reconstruction pass, this knowledge will be implemented by rotating the magnetic field (within its interface) such that $\mathbf{B_{rec}}=\mathbf{B_0(S_1x)}$, close to the true value of $\mathbf{B_{true}}=\mathbf{B_0(S_0x)}$ – see Figure 1 (right).

3.6 Measurement of the beam position and orientation

The position and orientation (tilt) of the beamline can be determined from the distribution of primary vertex positions, probably on a time scale of every few minutes during a fill. This information can be used to determine the time-dependent transformation **L** which transforms quantities measured in the reconstruction (in the GLOB frame) into the centre-of-mss frame with no p_T boost for analysis. Note that in the current CSC production, this transformation will simply be an identity, as no beamspot displacement, tilt or crossing-angle has been applied.

3.7 Interdependence of measurements

As there is no fixed absolute reference frame, and it is proposed that the calorimeter, muon, magnetic field and beamline positions all be measured with respect to the ID, care must be taken that the ID does not move in arbitrary directions during each alignment iteration. This could be done for example by constraining the mean position and rotation angle of all the ID elements to be unchanged after an alignment iteration. However, it is inevitable that as the alignment procedure evolves, modules and larger structures will move away from their surveyed positions, so that the effective GLOB coordinate system no longer exactly coincides with the real physical frame that the survey measurements were performed in.

A procedure must also be developed to ensure that the overall process converges, and that the calorimeter, muon and magnetic field alignments do not simply 'chase' changes in the ID alignment which move the positions of tracks extrapolated to the other detectors from one iteration to the next. One possibility would be to allow the individual system alignments to converge, then refit a reference sample of tracks with the updated constants to determine the global transformations linking the subdetectors. This would clearly be easier if such refitting could be done from ESD or even AOD information, without the need for a full reconstruction of the selected samples from RAW data.

4 Coordinate frames for reconstruction in real data

The situation for real data should be similar to that described for the CSC above, with initial coordinates of modules being expressed in the GLOB frame. However, analysis of the field map data may already allow an initial value for the field orientation $\mathbf{S_1}$ to be extracted, before any physics data. Similarly, the accuracy of survey information may well allow the first reconstruction pass to be with the 'best guess' alignment constants rather than starting from nominal (zero) values.

5 Coordinate frames for analysis

In the present offline software, no explicit distinction is made between the coordinate frame used for reconstruction and that used for analysis, in particular as most simulated data to date has not been produced with a beam tilt or crossing angle (even though the tools for doing this are now available – e.g. the event-boosting package from Esben Klinkby [2])

It may be desirable to transform all physics quantities in the analysis data model (on AOD and beyond) into the BEAM frame. This would ensure the physics events really have p_T=0, with no transverse boost. Correcting for the beamspot position would also mean that quantities such as impact parameters would have more meaning when expressed relative to the coordinate system origin. Against there, there are arguments concerning the additional complexity and risk of confusion, and possible difficulties in interpreting e.g. instrumental effects in missing E_T, which will actually be measured in the GLOB reconstruction frame (particularly in the trigger).

The crossing angle between the LHC beams is expected to be about 150μrad, e.g. 75μrad between each beam and the GLOB frame. For a 7 TeV proton this corresponds to around 0.5 GeV p_T in GLOB, but for a 100 GeV parton it would only be 7 MeV – probably negligible in comparison to systematics in the missing E_T measurement. Similarly, misalignment of the GLOB reference frame with respect to the beam frame might be around 300 μrad (corresponding to a ±1mm displacement at z=±3m at the end of the barrel cryostat), giving 30 MeV p_T on a 100 GeV parton. For most analyses, these effects may be completely negligible, and they may only be important for particularly challenging studies such as the W mass measurement.

If it is decided to do analysis in the BEAM frame, a natural place to implement this would be at the AOD level, so 'particle' objects (Electron, Muon, TrackParticle, JetTag etc) implementing an I4Momentum interface would return such 4-momenta in the BEAM frame. For the tracking, this is reasonably transparent, as a clear distinction is already made between the tracking parameter objects (q/p, ϑ, ϕ and a vertex) used in track reconstruction, vertex finding and b-tagging, and the AOD TrackParticle (p_x, p_y, p_z and derivable ϑ, ϕ) used in subsequent analysis. However, not all users are aware of the different meanings of the angles ϑ, ϕ in these two cases, and may be surprised when they become slightly different. For the calorimeter, the issue may be more complex, as both AOD analysis and ESD reconstruction objects are described primarily in terms of (η,ϕ), and these would then have different meanings on AOD and ESD. This may be particularly difficult in the context of the 'split-store' concept being explored to allow more cell-level calorimeter information to be stored on the AOD.

At present, the issue of whether to rotate analysis-level objects into the BEAM frame is left open, pending further discussion.

6 Software implications for release 13 and beyond

For reconstrucion, the above scheme has relatively small implications for the present software. The main issue is to go through the calibration and alignment challenge exercises, and demonstrate that the global misalignments between the different detector pieces can actually be dealt with in a coherent way, and the alignment procedure can be made to converge, at least in principle. Since the majority of the events are being generated with no beamline offset or tilt, it will be useful to simulate and reconstruct some samples with these effects (this is being planned for pixel/b-tagging studies). Ideally, any problems found should be fixed in time for release 13.

For the analysis coordinate frame issue, more work may be required:

- Some studies should be done to determine the magnitude of the problem, i.e. to identify analysis scenarios where the beamline tilt, offset and crossing angle actually make a difference and need to be taken into account.
- The conditions database interface for the beamspot position and tilt is already available (BeamCondSvc in InDetConditions). This needs to be expanded to also

include the crossing angles (in horizontal and vertical planes), and methods should be provided to transform 4-vector quantities into the BEAM frame.

- If it is decided to go ahead with the transformation to GLOB, the AOD contents will have to be reviewed to determine which quantities need to be transformed. The detailed implications for the AOD building tools will then need to be considered, as well as the process of moving data objects and analysis algorithms back and forth between ESD and AOD formats.

For all these issues, release 13 is probably too ambitious, and a full implementation (if needed) will have to wait for release 14.

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[1] L. Chevalier and D. Froidevaux, Detector description requirements for DC3, ATLAS EDMS document ATL-I-IR-0001, https://edms.cern.ch/document/794621

[2] E. Klinkby, EventBoost package in offline/Generators/GenAnalysisTools/EventBoost .