Rules and Guidelines for Manual Classification of Fixations, Saccades, PSEs and Other Events in High Quality Eye Movement Recordings During Reading.

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Abstract

We present a set of detailed scoring rules and the design of a scoring interface for the purpose of classifying eye-movements during reading. The recordings we employed were from the EyeLink 1000 and were collected at 1000 Hz. The subjects were reading a poem during eye movement recording. The rules and interface design emerged from a series of 20 consensus discussions between 3 graduate students and 1 faculty-level person with much experience studying eye movements. The discussions lasted, on average, 2.14 hours each. From 1-5 pilot classification attempts, made by the first four authors above, were performed between discussions. The events classified included saccades, post-saccade events (PSE), various artifacts, and by default, fixation. The rules are described in detail, with many illustrations. We are not aware of any other comparably detailed publicly available set of eye movement classification rules.

General Introduction to the Scoring Rules

Prior to scoring, or even understanding our scoring rules, it is necessary to be familiar with several scoring interface features (Figures 1 - 3). Please take a moment to study these three Figures and their captions. They will introduce you to the major features of our scoring page display. The formal rules refer to these features and are more understandable if one is familiar with them.

The scorer is responsible for deciding if a saccade is present and marking the start and end of each saccade. We also mark post-saccadic events (PSEs) which are commonly referred to as post-saccadic oscillations (PSOs). When referring to PSEs, we will use the term "signal change" rather than eye-movement considering the issues regarding PSE origin [3]. PSEs are signal changes that occur after the end of saccade and before the resumption of fixation. Many times, after a saccade ends after overshooting fixation, there is signal change in one direction only, so there is no oscillation. That is the difference between PSO and PSE: PSE includes such one-direction signal changes after a saccade end, as well as apparent oscillations (wave-like smooth signal change which is usually referred as PSO). To be scored as a PSE, the scorer must be convinced that there is some kind of signal change intervening between the end of the saccade and the resumption of fixation. Since PSEs, if present, always start on the next sample after a saccade ends, the user only has to determine the end of the PSE. The start is marked automatically.

Another event type we mark is noise. We distinguish 2 kinds of noise: Blink Related Artifact (BRA) and RIONEPS [1]. Partial non-fixation events at the start or end of the recording are scored as Unclassified (also see Figure 3). The scorer does not mark the start and end of fixation periods. All samples that are not saccade, PSE, BRA, RIONEPS or Unclassified are labelled as fixation by default.

The data we are scoring is from an EyeLink 1000 (SR Research, Ottawa, Ontario, Canada) while subjects read a poem. Typically, the saccades during this task are small saccades moving horizontally from left to right, word to word, or larger horizontal saccades taking the eye to the beginning of the next line of text. We formally define oblique saccades as saccades where the movement in both the horizontal (x) direction and the vertical (y) direction is at least 0.5 degrees of visual angle (Figure 2). We have an indicator (a magenta dashed line) which appears in the position (top) panel when movement (over the last 30 samples) in both the horizontal and vertical direction first becomes greater than 0.5 deg.

Wavy Saccades

The subjects in this study were performing 7 different eye-tracking tasks (6 in addition to this poetry-reading task) in a "session", with 2 sessions on each day, separated by a median of 19 minutes. Since the recordings were chosen randomly from session 1 and session 2, and since there were so many oculomotor tasks, subjects often became fatigued. During fatigue, what would normally be a saccade is often comprised of one or more "overlapping" saccades, as pointed out by Bahill and Stark [2]. As Bahill and Stark noted, such compound saccades do not follow the main sequence. We therefore classified such saccades as "wavy saccades", allowing subsequent analyses to distinguish these events from regular saccades (Figures 4 and 5). Wavy saccades are indicated by marked peaks and troughs in the velocity trace throughout the "saccade". We did not try to mark the start and end of each overlapping saccade since we did not think this could be done reliably. For scorer event-level reliability statistics in the associated manuscript, wavy saccades were treated as ordinary saccades.

Scoring Saccades

See Table 1 for saccade scoring rules. Another general point to make is that when marking the start and end of a saccade or the end of a PSE, the goal is not to include any sample which should belong to a period of fixation. The first sample chosen for a saccade should be the first point where the eye has moved away from fixation. If a saccade ends in fixation, the saccade end should be marked as the last point with "relevant" movement. The end of a PSE is the last point before the eye returns to the "fixation" state.

Scoring PSEs

See Table 2 for PSE scoring rules.

Scoring Blink-Related Artifact (BRA)

When the Eyelink 1000 cannot measure a gaze position, the device returns a NaN for that sample. These are almost always due to blinks. Blink-related artifact almost always include this period with NaNs (shown in the position trace as exactly 0 degrees). BRA also includes all samples around it that can't be considered as a fixation. The radial velocity channel as well as the position channel is used to determine the start and end of the BRA. Portions of the signal where the radial velocity noise is too high for fixation and eye position has not returned to the fixation level are all included in the BRA event. Note, that partial blinks (blink-like unnatural behavior of the signal without missing samples) are also labeled as BRA (see Figure 15). When choosing the start and end of BRA, we focus on the position trace and the radial velocity trace. We want to find the point where the signal begins to be affected by the BRA and where it ends being affected by the BRA. We choose these periods to remove any possible contamination of the signal by the BRA, and err toward the side of being overinclusive, rather than underinclusive, in determining the start and end of BRA.

Scoring RIONEPS

The goal here is to exclude any region of the recording that is affected by a RIONEPS. The start and end of each period affected by RIONEPS noise is marked. See [1] for examples and explanation of RIONEPS noise.

Scoring Unclassified Events

If recording starts or ends in the middle of any non-fixation event then this "partial event" is labeled as Unclassified (see Figure 3). If a saccade or PSE is interrupted by out-of-range values, the interrupted event is considered unclassified. This is true for events preceding and following out-of-range values. The scorer marks from the beginning of the event to the beginning of the out-of-range segment as unclassified and from the end

of the out-of-range segment to the end of the partial event as unclassified. If there is a complete PSE after an out-of-range section of data, that PSE must also be considered as unclassified, since, in our system, a PSE must be immediately preceded by a saccade. We do not mark unclassified events that occur during a BRA, regardless of the presence or absence of out-of-range values. All signal during a BRA is considered BRA only.

References

1. E. Abdulin, L. Friedman, and O. V. Komogortsev. Method to detect eye position noise from video-oculography when detection of pupil or corneal reflection position fails, 2017.

2. A. T. Bahill and L. Stark. Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system. *Exp Neurol*, 48(1):95–106, Jul 1975.

3. M. Nyström, I. Hooge, and K. Holmqvist. Post-saccadic oscillations in eye movement data recorded with pupil-based eye trackers reflect motion of the pupil inside the iris. *Vision Res*, 92:59–66, Nov 2013.

Tables

Table 1. - Steps in the Scoring of Saccades

★ **Rule for small saccades.** We are not scoring microsaccades. Very small saccades (< 0.5 deg amplitude) are not scored

★ **Determine if the saccade is oblique or not.** If there is significant movement (i.e. 0.5 degrees) during a saccade in both the horizontal and vertical channels then the saccade is considered oblique. This choice determines which velocity trace is to be considered when determining the start and end of the saccade. If the saccade is not oblique than the relevant velocity is the velocity of the dominant direction and one of the traces in the middle panel is used. If the saccade is oblique then the radial velocity in the lower panel is used.

★ **Determine if the saccade is a "wavy saccade".** Wavy saccades consists of two or more marked velocity peaks and troughs during the saccadic movement itself. We are more inclined to score a wavy saccade if the velocity peak of the overlapping saccades is near 75 deg/sec (Figure 6)

★ **Determining the start of a saccade.** To determine when a saccade starts the scorer focuses on the relevant velocity trace [middle panel (horizontal trace) middle panel (vertical trace) or bottom panel]. If the saccade has a dominant direction the scorer finds the first point where the velocity is moving in the direction of the saccade (Figure 7). The scorer then looks to find the first sample in the direction of the saccade where there has been a substantial change in the velocity (acceleration is change in velocity) (Figure 7). If this point does not also look correct in the position trace the scorer needs to adjust the start to be more consistent with the information in the position trace. For saccades that need to be scored with the radial velocity trace the scorer is attempting to find a similar starting point as above without the benefit of a directional indicator. That is, pick the point in the vicinity of the start of the saccade where there has been a substantial change in the velocity (acceleration).

★ **Determine the end of a non-oblique saccade** At first, the scorer must find the last consecutive point with movement in the same direction as the general saccade movement. To illustrate (see Figure 7) suppose that the dominant direction of the saccade is rightward (horizontal upward in the position channel). The relevant velocity trace is the horizontal velocity trace in the middle panel.

- • **Rule 1:** The last black dot in this velocity signal in the vicinity of the saccade end is chosen as the saccade end.
- • **Rule 2:** If this point in the scorer's judgement marks an unreasonable endpoint for the saccade then try one point prior to the local velocity minimum (see Figure 8).
- • **Rule 3:** If this is not a reasonable end of the saccade then the user must make his best judgement based on the dominant position trace and the relevant velocity trace giving equal weight to each (see Figure 9).
- • One general guideline in choosing the end of a saccade is that the saccade ends only after a subsequent fixation level is reached or nearly reached. Another general guideline is to choose a point immediately preceding a local velocity minimum where there has been a marked deceleration. This point should look correct both in the relevant velocity trace and the position signals.
- • When deciding a local minimum, if several consecutive points all have very low but very similar values you can treat them all as one local minimum.

★ **Determine the end of the saccade – oblique saccades.** For oblique saccades the radial velocity channel is used. The end of the saccade should be a point prior to a local velocity minimum where there has been a marked deceleration. This point should look correct both in the radial velocity trace and the position signals (see Figure 10)

★ **Some saccades have very slow endings.** In Figures 11 and 12 we illustrate two saccades with very slow endings. While not frequent, we do see such endings on saccades. The final slow drifting part of the saccade is included in the saccade

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Table 2. - Steps in the Scoring of PSEs

★ **Is PSE Present?** The scorer needs to decide if a PSE is present basing his/her judgement on the following:

✓ The decision about whether or not there is a PSE is made viewing the both the position and velocity trace.

✓ PSE has to occur right after the saccade and is never chosen after an intervening period of fixation in the position and velocity trace.

✓ PSE can manifest in 3 forms:

- Single-directional corrective movement. A movement that returns an eye to the fixation level, after a saccade passes the fixation level is a PSE of the first form.
- Wave-like smooth signal change (PSO).
- A combination of previous two.

★ **PSE Start** The start of a PSE is, by definition, the first sample after a saccade.

★ **Which Velocity:** If there is clear evidence of a PSE in both channels, the scorer should use radial velocity (See Figure 13). If the PSE is only clear in one position trace, the scorer is to use the middle velocity panel, and the velocity for the trace where the PSE is clearly evident is chosen (horizontal or vertical).

★ **The End of the PSE:** The scorer points to the best estimate of the end of the PSE in the position traced. The scorer then looks at the relevant velocity trace and chooses the last point in this vicinity that has a velocity higher than an estimate of subsequent fixation maximum velocity (excluding unusually large velocity peaks). (Illustrated in Figure 14).

Figures

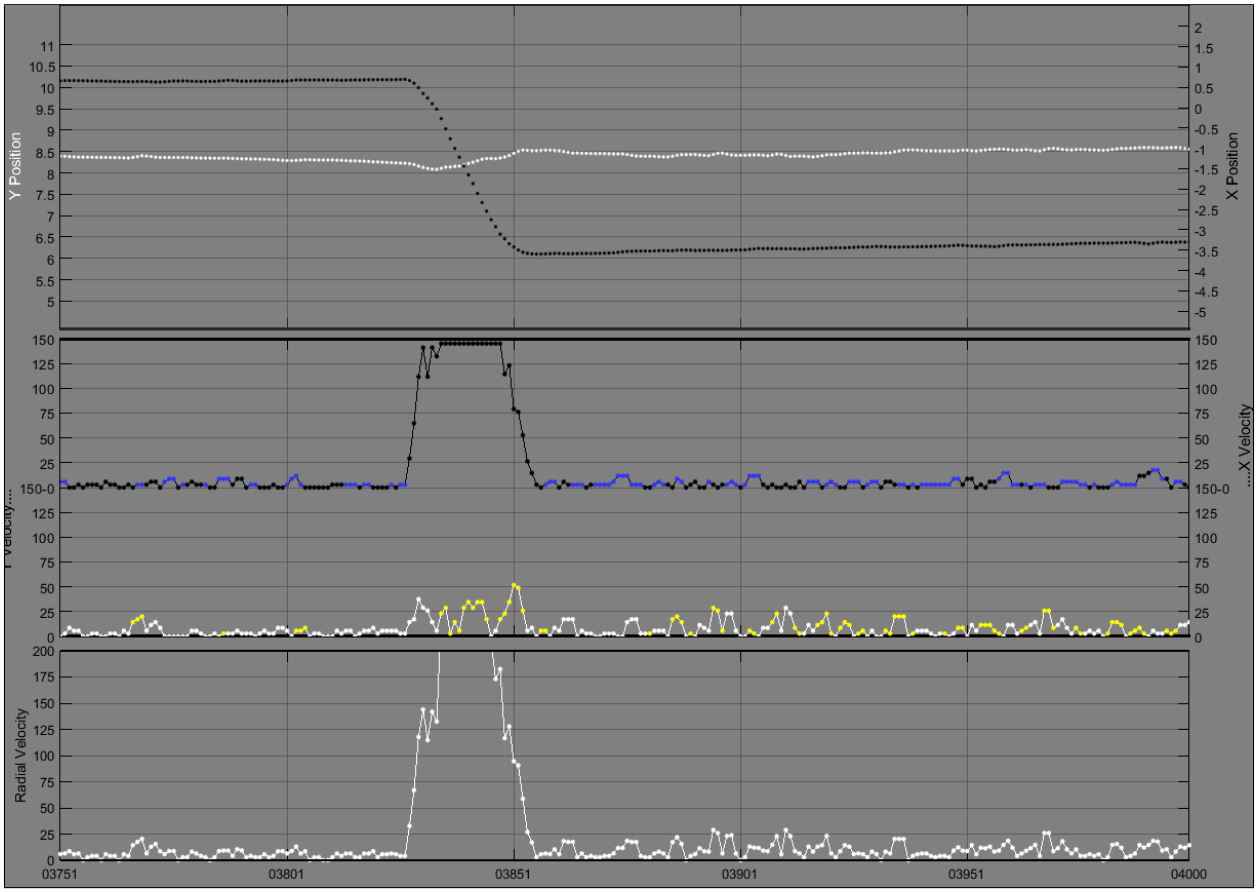

Figure 1. Scoring Page. This is an example of what the scorer sees when making event start and end decisions. The top panel presents the position signals, with the horizontal position ("X") shown in black dots and the vertical position ("Y") shown in white dots. Both the horizontal position and the vertical position are always plotted to have the same range. The minimum range for position signals is 7.5 deg. The horizontal gridlines in the top panel are always 0.5 deg apart. The middle window presents the instantaneous velocities for the horizontal signal ["X", x(i)-x(i-1), shown with black lines], and vertical signal [white lines]. For both x and y, only abs(velocity) is plotted, and both are clipped at 145 deg/sec. When the horizontal position change is positive (moving to the right), the dots are blue, but when it is negative, the dots are black. When the vertical position change is positive (moving up), the dots are yellow, but when it is negative, the dots are white. The lower panel displays the instantaneous radial velocity (also known as angular velocity), shown in white. $v_r = \sqrt{(v_x^2 + v_y^2)}$, where v_r is radial velocity, v_x is velocity in the horizontal direction, and v_y is velocity in the vertical direction. Our monitors were all set to a 4:3 aspect ratio to homogenize the appearance of the scoring page.

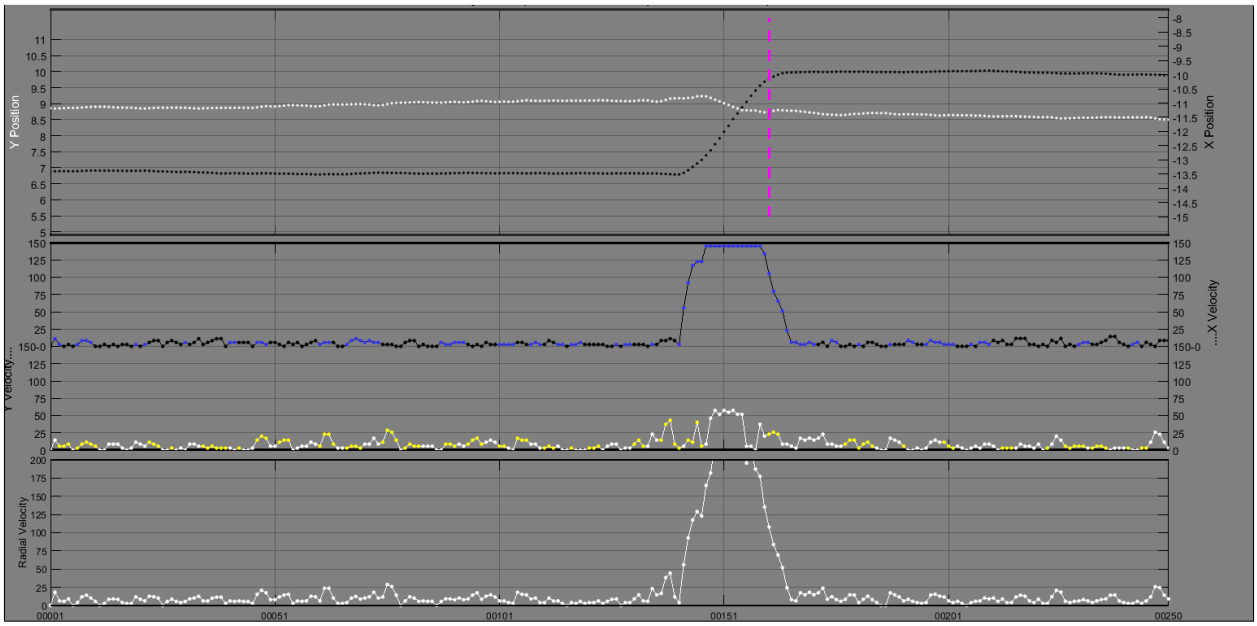

Figure 2. Example of an Oblique Saccade: We define oblique saccades as saccades where the movement in both the horizontal direction and the vertical direction are both greater than 0.5 degrees. The magenta dashed line in the position panel (top panel) marks the point when, over the last 30 samples, there has been a change of at least 0.5 degrees in both the horizontal (black) and vertical (white) eye position signals. If this magenta line occurs in a saccade, this is an indication that this event appears to be oblique. This indicator does appear after other events such as PSOs and also during blink-related artifact. It is an indication that the scorer should consider using the rules for scoring oblique saccades (see below). It is still up to the scorer's judgement whether or not the indicated event is truly an oblique saccade.

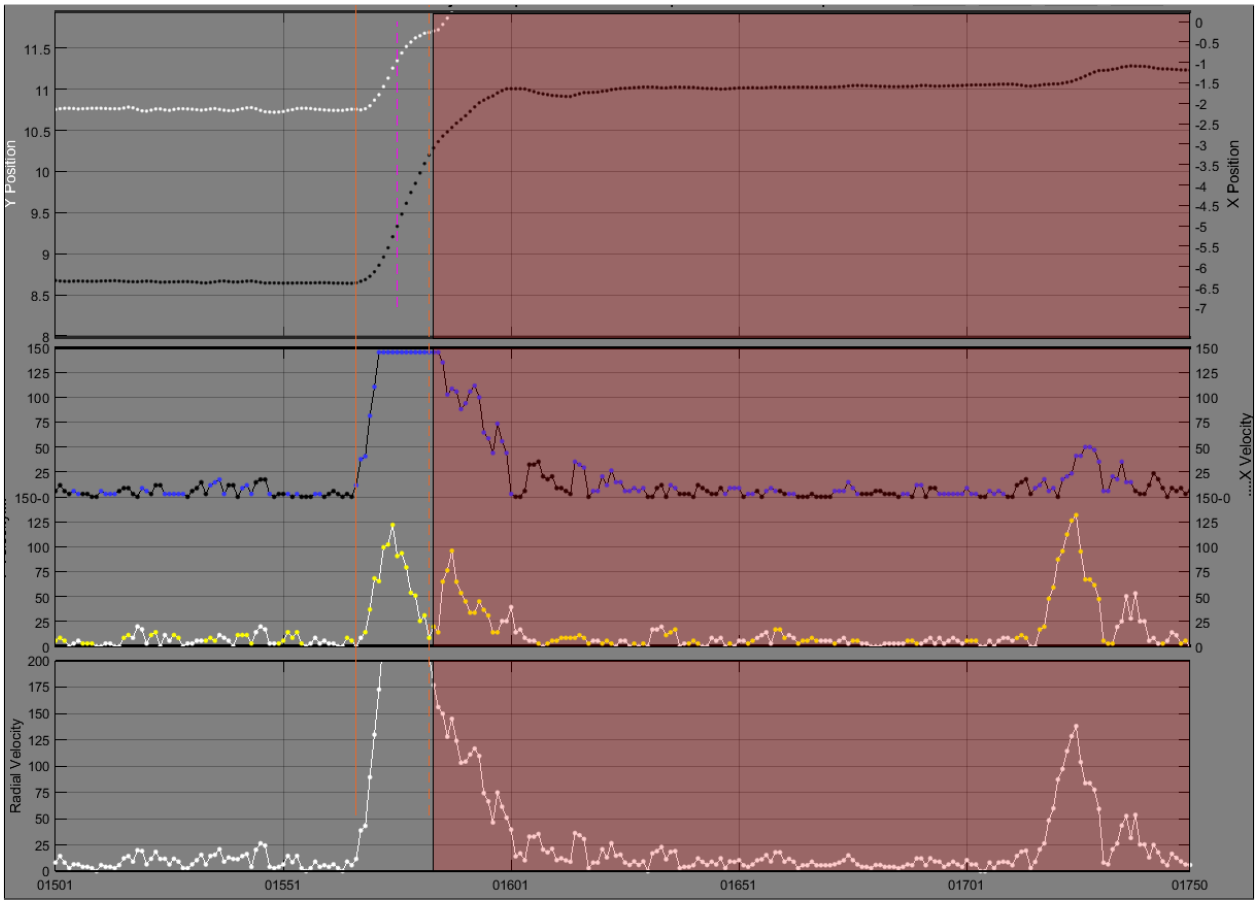

Figure 3. Illustration of how the program handles out of range data. The degrees of visual angle for our display during eye-movement recording ranges from -23.3 to 23.3 deg horizontal and from -18.5 to 11.7 deg vertical. We are not interested in scoring eye-movement data when the viewer is not looking at our display screen. Such regions of recording are overlaid with a transparent red color. There is a partial saccade just before the out-of-range data, and this event is marked as "unclassified" (see orange vertical solid and dashed lines just before the out-of-range section)

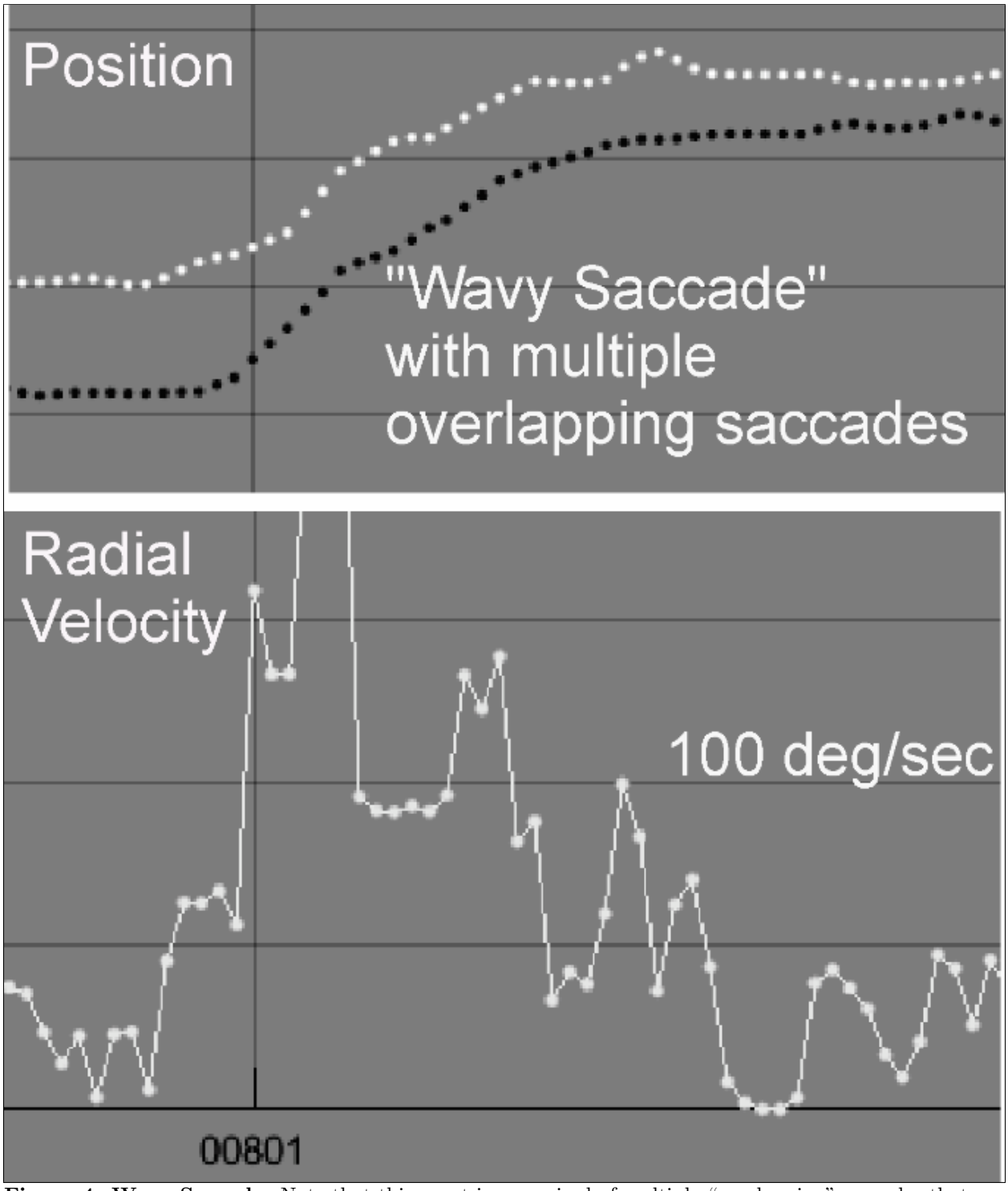

Figure 4. Wavy Saccade: Note that this event is comprised of multiple "overlapping" saccades that are obvious in the position trace. Note the multiple marked peaks and troughs in the radial velocity trace during this event. This is event is very similar to examples shown in the Bahill and Stark report [2], but is not typical of what we see. A more typical example is shown in Figure 5.

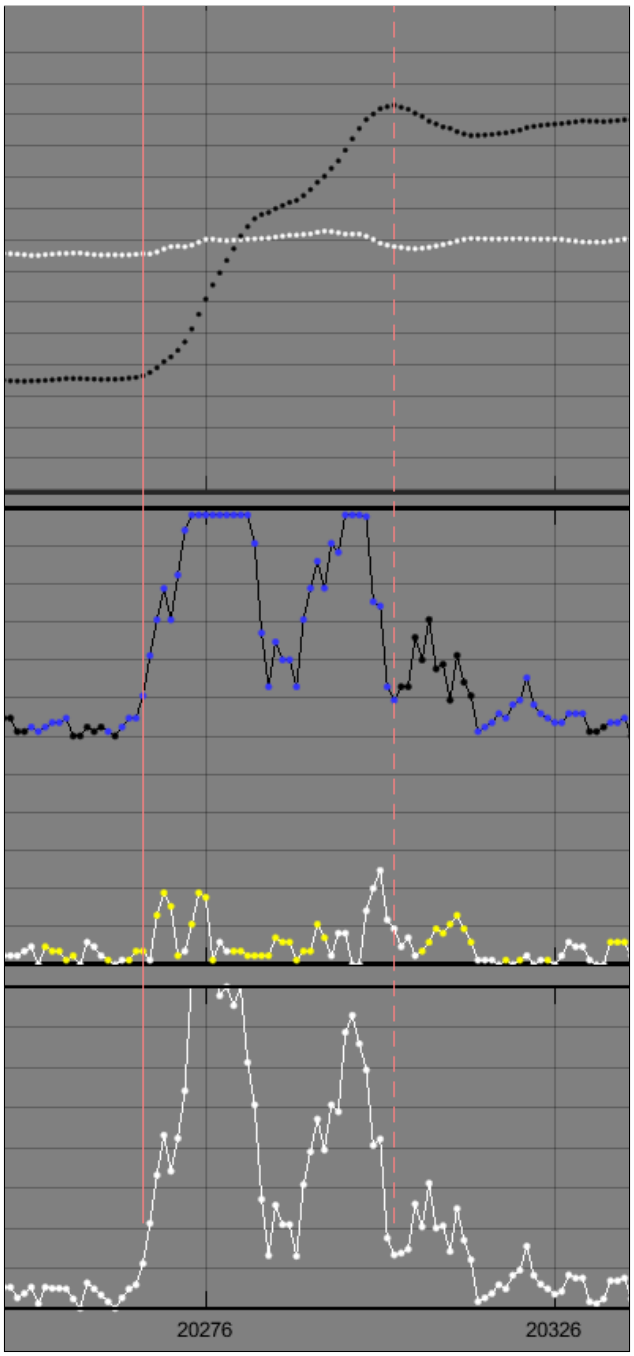

Figure 5. A more typical "wavy saccade".

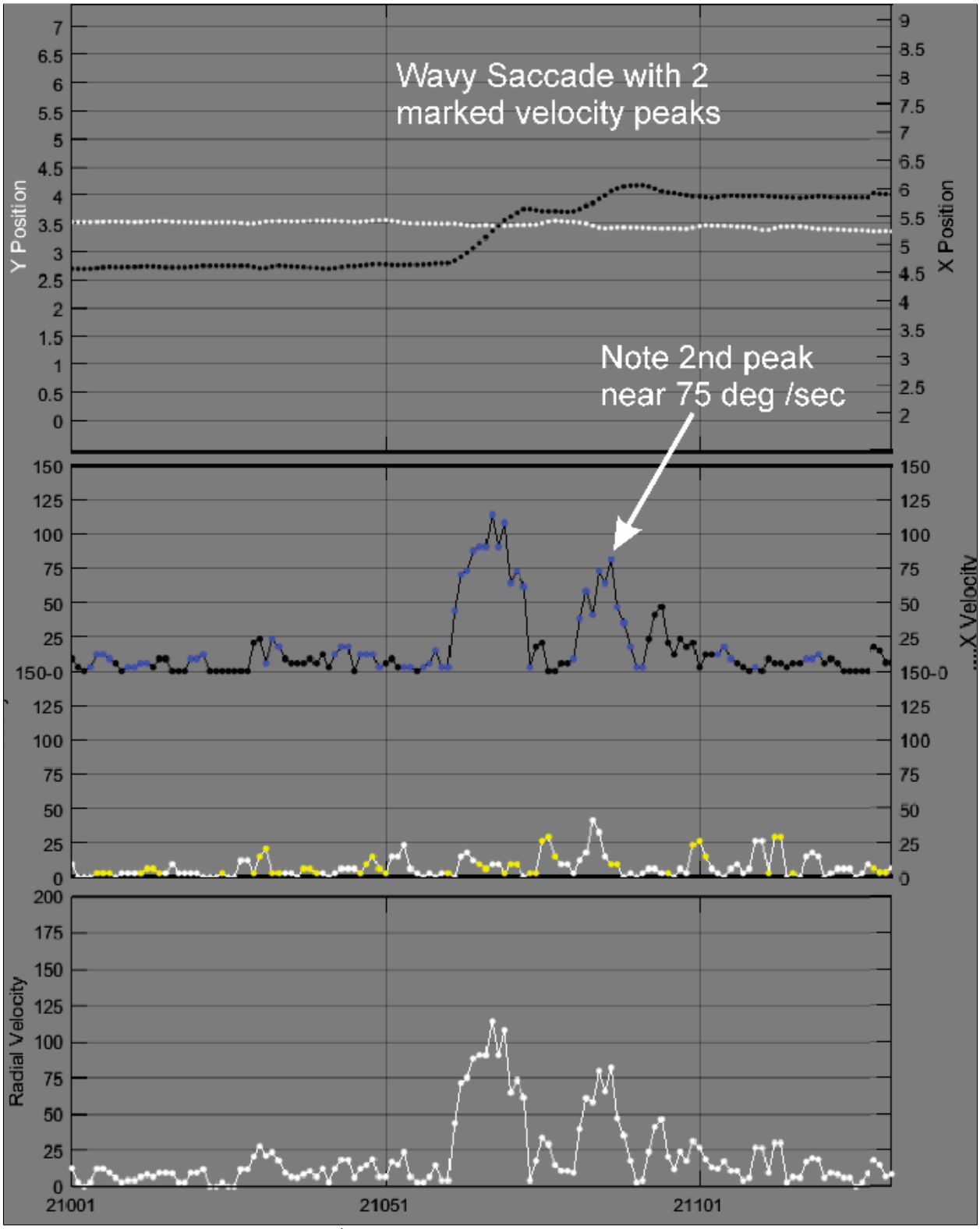

Figure 6. Illustration of 75 deg/sec rule for wavy saccades. If an overlapping saccade has a peak velocity above 75 deg/sec, this should weight your judgement toward referring to the entire event as a "wavy" saccade.

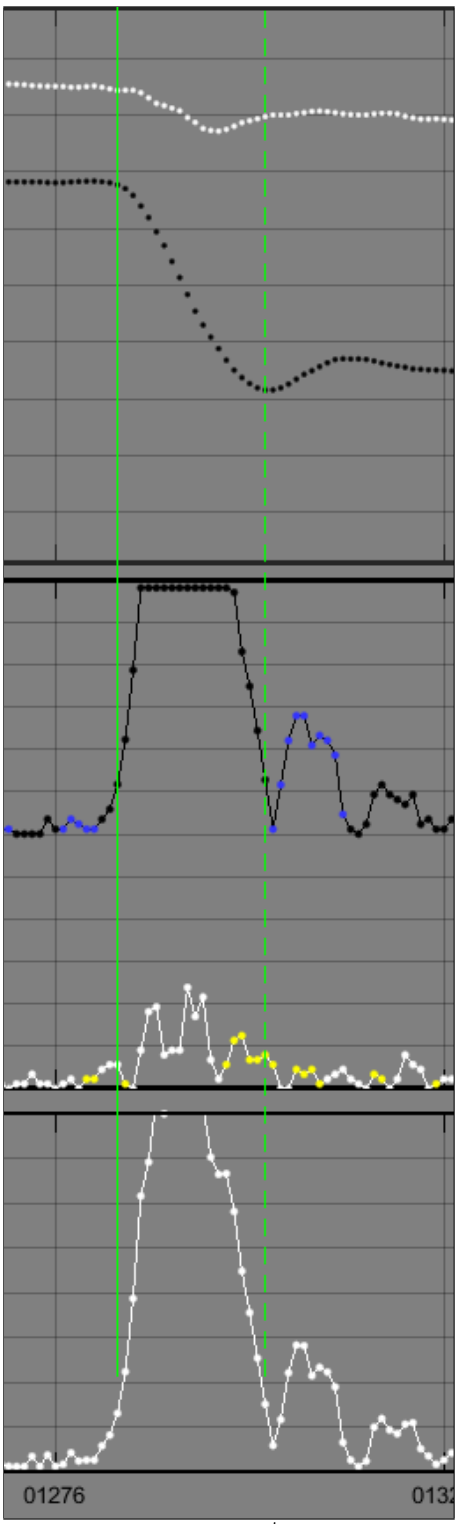

Figure 7. Saccade end marked according to the 1st rule. Since the movement in the vertical channel is less than 0.5 deg, this is not an oblique saccade. This is a leftward 2.0 deg saccade. The end is marked according to saccade-ending 1st rule

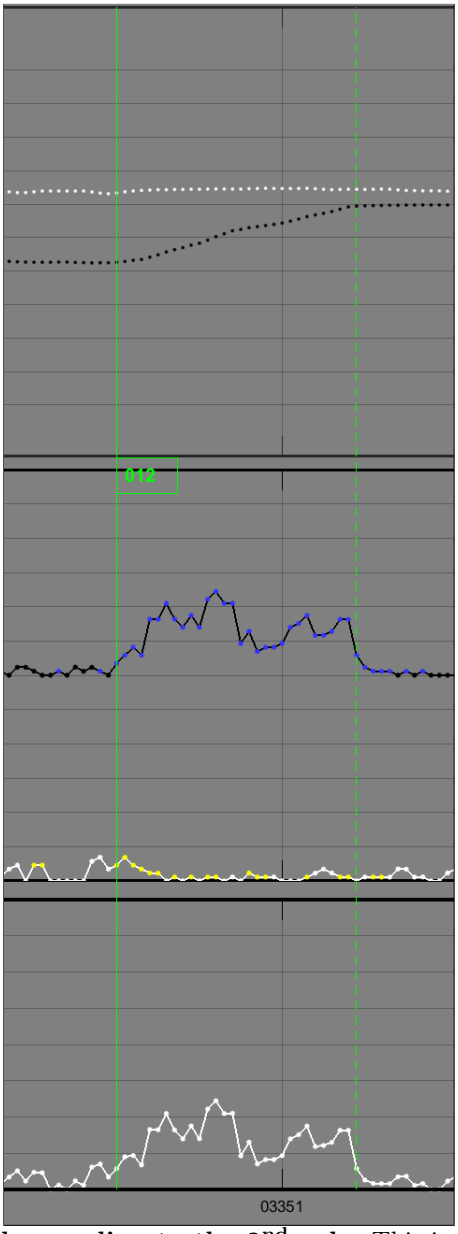

Figure 8. Saccade end marked according to the 2nd rule. This is a rightward 1.0 deg saccade. Note that the movement in the vertical direction (white dots in upper trace) is less than 0.5 deg amplitude, and therefore meets our criteria for a non-oblique saccade.

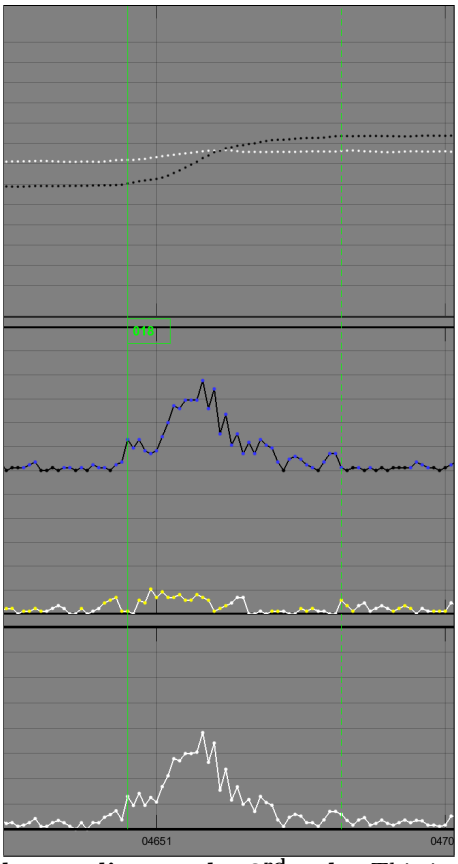

Figure 9. Saccade end marked according to the 3rd rule. This is a rightward 1.0 deg saccade. Note that the movement in the vertical direction (white dots in upper trace) is less than 0.5 deg amplitude, and therefore meets our criteria for a non-oblique saccade.

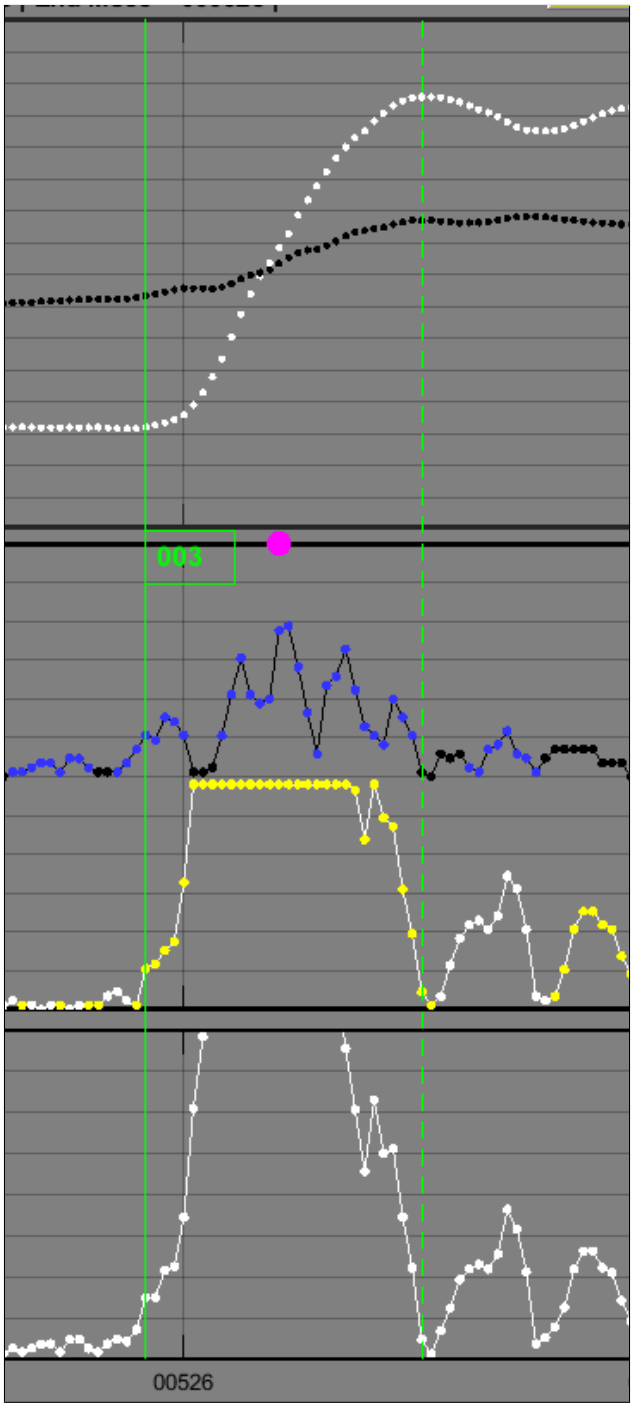

Figure 10. Oblique saccade with start and end marked.

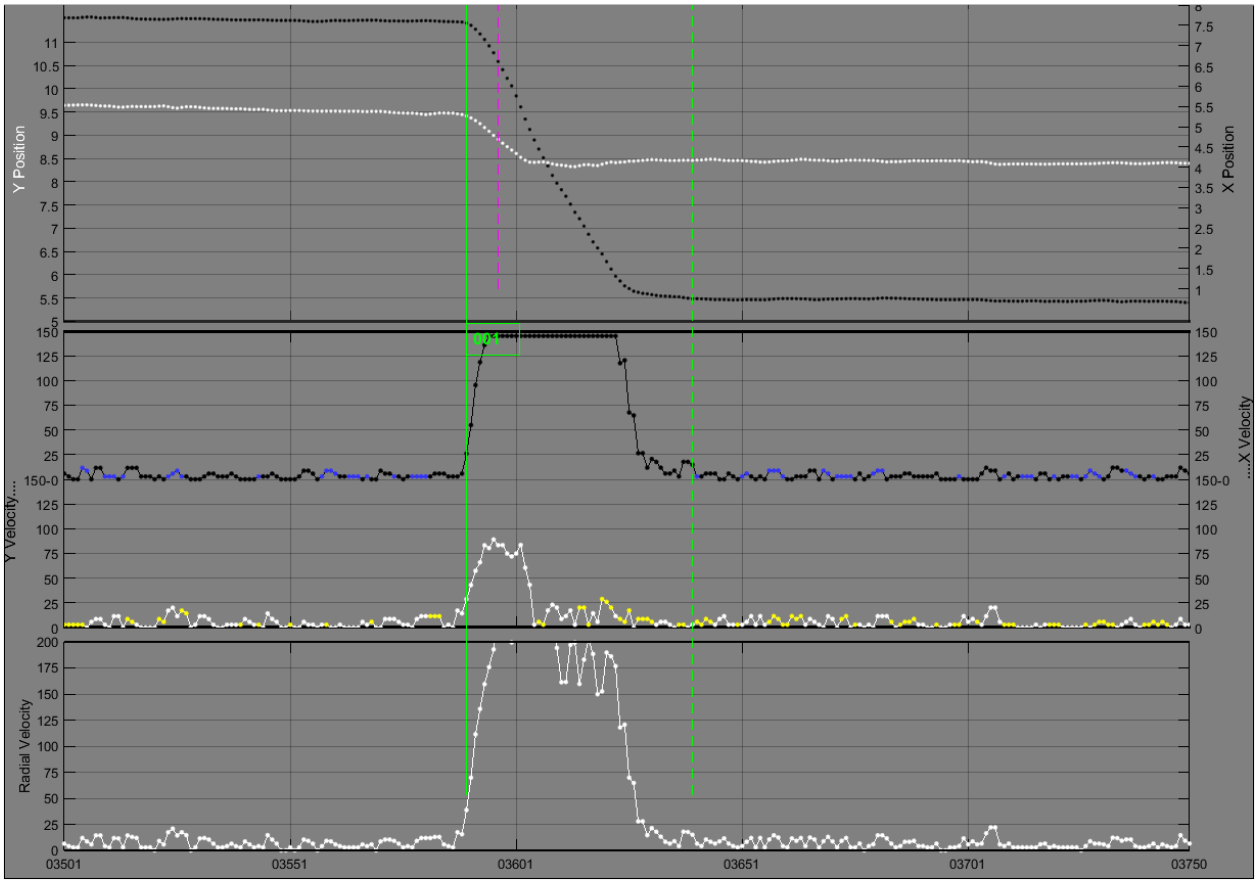

Figure 11. Large, slowly ending saccade marked correctly.

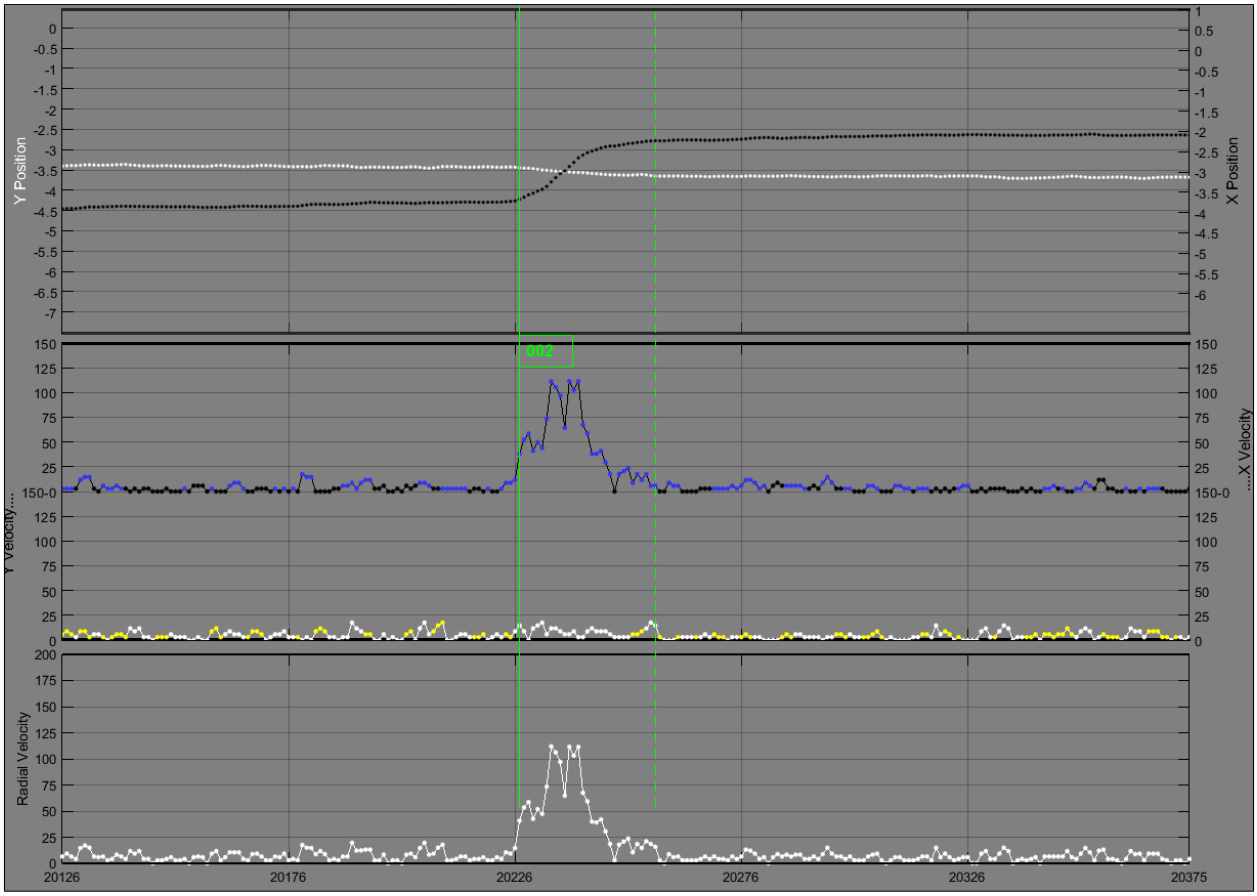

Figure 12. A small, slowly ending saccade.

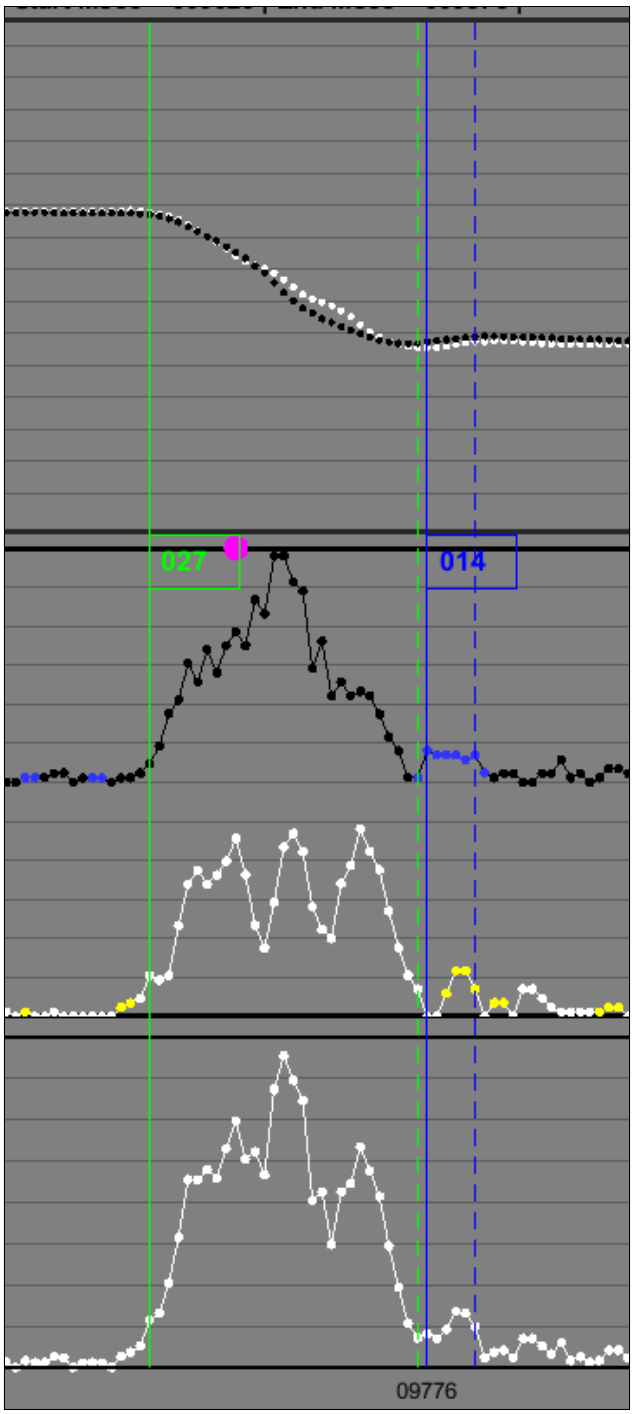

Figure 13. Marking the End of a PSE. This oblique saccade is followed by PSEs in both channels. The scorer should use radial velocity. The scorer chooses the last point in that has a velocity higher than an estimate of subsequent fixation maximum velocity (excluding unusually large velocity peaks).

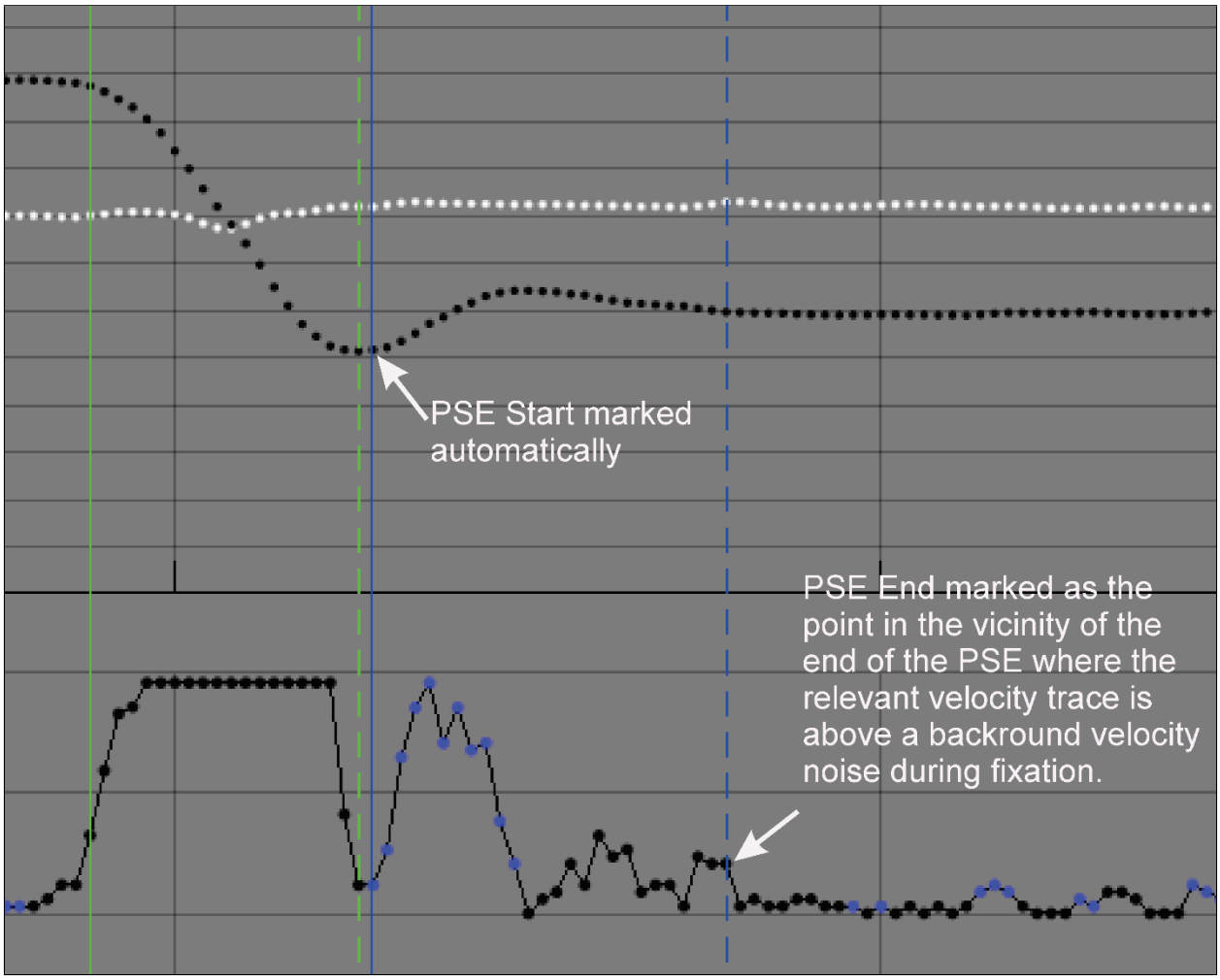

Figure 14. Marking the End of a PSE. The non-oblique saccade prior to the PSE is marked according to the main rules. The start of the PSE is the next sample after the end of the saccade. The scorer uses his judgement to determine the vicinity of the PSE end using both the relevant velocity and position traces. The exact point chosen is the last point in this vicinity where the velocity signal is above background fixation velocity noise.

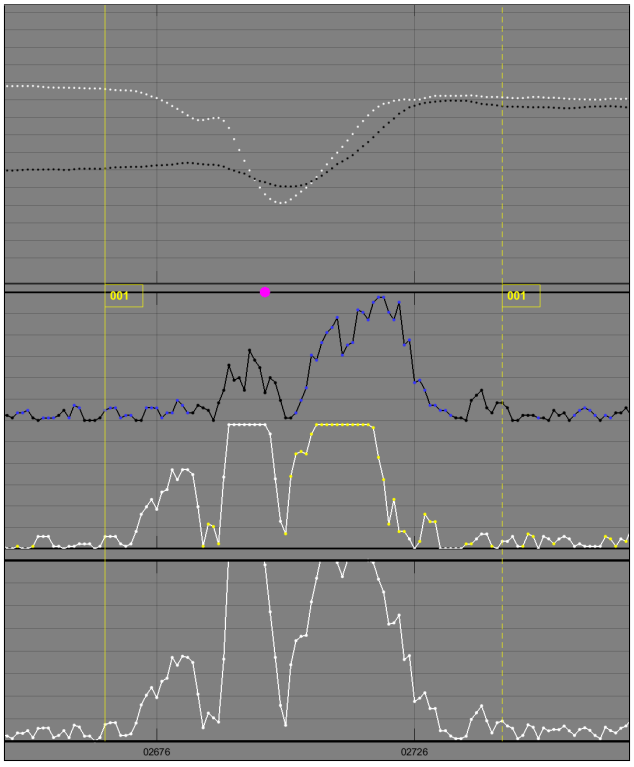

Figure 15. Blink-related artifact that does not contain any NaNs. The BRA event stats with the left vertical yellow line and the BRA event ends at the right vertical yellow line.