A Robust R-peak Detection Algorithm using Wavelet Packets

Omkar Singh
School of Electronics and Communication Engineering Lovely Professional University Punjab-INDIA

Ramesh Kumar Sunkaria
Department of Electronics and Communication Engineering National Institute of Technology Jalandhar- INDIA

ABSTRACT
The efficient detection of R-peaks in electrocardiogram (ECG) signal is extremely important for its further processing with regard to cardiac health monitoring. In this paper, an efficient R-peak detection algorithm based on wavelet packets has been proposed. The wavelet packets decompose ECG signal into different frequency subbands of uniform bandwidth. The features evaluated from a set of subbands are combined with heuristic detection strategy for beat detection. The proposed R-peak detection algorithm was tested on different data records of standard data bases Fantasia database, MIT-BIH arrhythmia database and self-recorded signals. A sensitivity $S_e = 100\%$ and a positive predictivity of $+P = 100\%$ for Fantasia database and $S_e = 99.94\%$, $+P = 99.93\%$ for MIT-BIH arrhythmia database were achieved using this proposed algorithm.

Keywords
R-peak detection, ECG, Wavelet packets, sensitivity, positive predictivity.

1. INTRODUCTION
The ECG signal is a recording of electrical activity of heart. A single ECG cycle consists of P, Q, R, S, and T waves. The QRS complex and especially R-peak detection is the most prominent feature in the ECG signal and its accurate detection forms the basis of extraction of other features and parameters from ECG signal. Since the QRS complex varies with different cardiac health conditions, therefore efficient and automatic detection of QRS complex and R-Peak is essential for reliable health condition monitoring. Many algorithms have been developed during the last five decades for accurate and reliable detection of R-peaks in the ECG signal indicating high percentages of correct detection, which are classified as syntactic, non-syntactic, transformative and hybrid algorithms. The earlier QRS complex detection algorithm involve a preprocessor stage, where the ECG signal is transformed to accentuate the QRS complex, and a decision stage, where a QRS complex is detected using thresholding, yielded 99.3% detection accuracy [1]. This was further improved to a detection accuracy of 99.67% [2]. A QRS detection algorithm using hardware filter banks was proposed which reported sensitivity of 99.59 % and positive predictivity of 99.56 % against the MIT-BIH Arrhythmia Database [5]. A wavelet transforms based QRS detection algorithm was proposed which reported 0.15 % false detections [7]. A new wavelet based QRS detection algorithm was developed which yielded very high detection accuracy of 99.99% [6]. In the present work a R-peak detection algorithm based on wavelet packets has been proposed. The wavelet packets based algorithm decomposes the ECG signal into different frequency subbands. Features which are indicative of QRS complex is designed by combining a set of subbands. These frequency bands are then combined to give the overall beat detection, in contrast to a single channel analysis as in case of WT-based R-peak detection algorithm. The proposed WP-based QRS detection algorithm was tested on standard databases and self recorded signals. The algorithm was implemented in MATLAB.

2. METHODOLOGY
2.1 Signal analysis using wavelet packets
The analysis of signal using discrete wavelet transform (DWT) is done at different frequency bands with different resolutions by decomposing the signal into approximate and detail information through its filter bank consisting of low pass and high pass filter. The signal is down sampled by a factor of 2 at each level and this process is known as subband coding and it can be repeated for further decomposition of the signal as per requirement. This phenomenon of DWT implementation is illustrated by Figure 1. The wavelet packet decomposition is a generalization of wavelet decomposition which leads to more accurate signal analysis. Wavelet packets are waveforms indexed by three parameters of position, scale and frequency. In orthogonal wavelet decomposition process, the generic step splits the approximation coefficients into approximation coefficients and detail coefficients. The information lost between two successive approximations is captured in the detail coefficients. The next step is splitting the approximation coefficient vector of previous decomposition into detail and approximation coefficients. In corresponding wavelet packets based analysis; each detail coefficient vector is also decomposed into approximate and detailed coefficient vector similar to that in approximation vector splitting. This enables more accurate extraction of intended features of the signal.

2.2 The Proposed R-peak detection algorithm
The efficient detection of R-peak in ECG signal is extremely important for ECG signal feature extraction which leads to highly accurate cardiac health prognosis. The flowchart of the proposed R-peak detection algorithm has been shown in Figure 2. The details of each stage of the proposed algorithm have been described in the following sections.

2.3 The ECG signal Decomposition into frequency subbands using wavelet packets
The proposed R-peak detection algorithm based on wavelet packets decomposes the input ECG signal into different frequency subbands of uniform bandwidth. The subbands are downsampled by a factor of 2 at each level. The decomposed subbands provide information from various frequency ranges. The number of levels by which the input ECG signal is to be
decomposed, depends on sampling frequency of the input signal.

\[
\text{High Pass Filter} \quad \hat{g}(n) \quad \downarrow \quad \text{Detected signal}
\]
\[
\text{Input Signal} \quad x(n)
\]
\[
\text{Low Pass Filter} \quad \hat{h}(n) \quad \downarrow \quad \text{Approx. signal}
\]

**Fig 1: Implementation of DWT**

For example in case of MIT-BIH Arrhythmia database signals, the sampling frequency is 360 Hz. So, it is to be decomposed up to five levels as shown in Figure 3. In this case, the input ECG signal is decomposed into 32 frequency bands each having a bandwidth of 5.625 Hz. In case of Fantasia database the sampling frequency is 250Hz. Thus, the signal is decomposed up to four level only, which gives 16 frequency bands each of bandwidth 7.75 Hz. Similarly, the self-recorded signals which are sampled at 500 Hz are decomposed up to five levels resulting in 32 frequency bands each having a bandwidth of 7.75 Hz. Figure 4 shows an ECG signal and its decomposed frequency bands.

**2.4 Combining the subbands for Features extraction**

Multiple features are calculated by combining a set of subbands which indicate the QRS complex energy in various frequency bands. A sum-of-absolute values feature is computed using subbands 1 and 2.

\[
P_1 = \sum_{j=1}^{2} |w_j|
\]

The calculated feature \( P_1 \) indicates the energy of the ECG signal in the frequency band [5.6, 16.87] Hz. Similarly, \( P_2 \) and \( P_3 \) are computed using subbands [1, 2, 3, 4] and [2, 3, 4], respectively, and these values are proportional to the energy in their respective subbands. A detection logic is used to incorporate some of the above calculated features for accurate location of R-peak in the ECG signal.

**2.5 R-peak detection using multiple channels**

The objective of the R peak detection algorithm is to determine the accurate location of R-peaks in an ECG signal. In most of the R-peak detection algorithms based on wavelet transform, the input ECG signal is decomposed using DWT up to some appropriate level and then adaptive threshold is applied to the decomposed signal to locate R-peaks [6]. Since QRS complex energy varies with different morphologies and under different cardiac health conditions, therefore instead of using single channel for R-peak detection as in case of WT based algorithms, various frequency subbands are combined in WP based R-peak detection algorithm to enhance the detection efficiency of the algorithm. In WP based R-peak detection algorithm multiple channels with different False negatives (FN’s) and False positives (FP’s) detections are operated and the results of each are combined together to achieve an overall detection efficiency.

**2.5.1 Single channel detection**

In single channel detection a computed feature is input to a moving window integrator (MWI) which takes the average of two samples at the downsampled rate. Whenever a feature value is detected as a Signal (noise) peak, the signal (noise) value is stored. The signal (noise) level for each detected event is determined by computing the mean of the previous signal (noise) values using the two equations

\[
N_L = 0.9 \times \text{meanL1}
\]
\[
S_L = 1.1 \times \text{meanL1}
\]

For each detected event detection strength \( D_s \) is determined by comparing with the signal and noise levels \( (S_L \text{ and } N_L) \) with the feature valve.

\[
D_s = \frac{P - N_L}{S_L - N_L}
\]

When a feature’s value is less than \( N_L \) then \( D_s \) is set to 0, and if it is above \( S_L \) then \( D_s \) is set to one. When the \( D_s \) of a detected event is greater than a predefined threshold it is categorized as a signal peak and the signal history is updated with the feature’s value. When the \( D_s \) of a detected event is smaller than a predefined threshold it is categorized as a noise peak and the noise history is updated with the feature’s value. The \( D_s \) thus indicates whether the incoming feature is a signal or noise peak. If detection strength is close to one, then there is a greater possibility that the current peak is a beat, whereas if detection strength is close to zero then there is a greater possibility that the current peak is a noise peak. The detection strength factor is used in the overall R-peak detection logic.

**2.5.2 Levels**

Multiple channels with different threshold valves are operated on different features in the R-peak detection algorithm to achieve overall detection efficiency.

**2.5.2.1 Level 1**

In the first level [5] the event detector operated on feature \( P_1 \) detects a beat whenever there is an inflexion point in the output of MWI. The value of the detected peak is not compared to any threshold; rather it is used to trigger an event in the further levels. This level thus acts as an “event detector,” and is used to trigger further logic to eliminate FP’s and FN’s introduced here.

**2.5.2.2 Level 2**

This level, consists of 2 single channels (Chan1 and Chan2) operating simultaneously. Both channels use feature \( P_2 \) in their respective MWI’s, but their respective thresholds are different. Chan1 uses a low threshold \( (T_1 = 0.03) \) and Chan2 uses a high threshold \( (T_2 = 0.7) \). When the event detector detects an event, channel1 and channel2 are triggered and the output in the MWI’s of each of Chan1 and Chan2 are compared with their respective signal and noise levels. The signal (and noise) levels in each channel are computed from the signal (and noise) history of their respective channels. Detection strength for each channel is computed and is compared to their respective thresholds. Each channel classifies the current event as a beat or noise independent of the classification from the other channel. Whenever a channel detects an event (beat or noise peak) its own signal (or noise) history is updated irrespective of the detection status from the other channel.
Fig 2: Flowchart of R-peak detection algorithm

Start

Load ECG signal

If sampling frequency = 500 Hz

Y

Decompose ECG signal into frequency bands using wavelet packets at depth 5

For j=1:4 Read wavelet packet coefficients (5, j)

Evaluate features P1, P2, and P3 using sum of absolute values of wavelet packet coefficients

Moving Window Integrator

Event detector (operated on P1)

Channel 1 (operated on P2) Threshold = 0.03

Channel 2 (operated on P3) Threshold = 0.7

Combined detection using channel 1 and channel 2

Channel 3 (operated on P3) Threshold = 0.5

If interval of two RR-complexes < 0.24 => go back and delete one of them

Mapping of the detected R-peaks on the actual sample points of original signal

Stop

If sampling frequency = 360 Hz

Y

Decompose ECG signal into frequency bands using wavelet packets at depth 4

For j=1:4 Read wavelet packet coefficients (4, j)

If sampling frequency = 250 Hz

Y

N

N

N
In single channel detection, the threshold value determines whether the detected event is a signal peak or noise peak so this value should be chosen precisely. The algorithm described here is tested for different threshold valves and the specified threshold valves are found to be optimum. This level, thus, operates simultaneously two single channels which have complementary FN and FP detection rates. Chan1 outputs a few FN’s but many FP’s and Chan2 outputs many FN’s but a few FP’s. All computations are performed at the downsampled rate and this contributes to the overall computational efficiency of the R-peak detection algorithm.

2.5.2.3 Level 3
This level combines the beat detection classification from each of the 2 single channels in level 2 by including a set of if-then-else rules. The rules incorporate the fact that the 2 single channels have complementary detection rates. Four possible cases arise. If both channels classify the current event as a beat then the output status of level 3 is a beat. Since Chan 2 uses a high threshold, it produces few FP’s and, thus, beat detection is very accurate. If both channels classify the current event as a noise peak then the output status of level 3 is a noise peak.

2.5.2.4 Level 4
This level incorporates another single channel and uses feature $P_3$ as the input to the MWI. If level 3 indicates a beat, the signal history is updated and the detection status from this level is that the current event is a beat. If level 3 classifies the event as a noise peak, the detection strength of the channel 4 is computed and compared with the threshold ($T_4 = 0.5$ for this channel). If the detection strength is greater than the threshold the current event is classified as a beat and the signal history is updated. If the detection strength is less than the threshold the noise history is updated and the current event is classified as a noise peak. This leads to improved detection rates.

2.5.2.5 Level 5
If a beat was detected during the refractory period (240ms) (with reference to the previous beat detection) and also had minimal detection strength in level 4 ($D_{s4} \leq 0.05$), then the status of the event is changed from a-beat to a noise peak. If the interval between two RR complexes is too long a search-back technique is used to look back in time for the QRS complex with low threshold (0.02).

Fig 4: Input ECG signal and its decomposed frequency subbands
indicating which decision was “stronger,” is compared to favor the channel with the stronger decision. The detection logic is summarized as follows:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Decision 1</th>
<th>Decision 2</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan1</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Chan2</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Output</td>
<td>✓</td>
<td>✓</td>
<td>Δ₁?Δ₂</td>
</tr>
</tbody>
</table>

Where $Δ₁?Δ₂$: if $Δ₁ >$ then ✓ else ×

$Δ₁ = (D_{s1} - T₁) / (1-T₁)$

$Δ₂ = (T₂ - D_{s2}) / T₂$

($✓$: a-beat; $×$: a noise peak)
2.6 Mapping of the detected R-peaks on the actual sample points of original signal

The detected R-peaks are fiducial points of the downsampled signal and these are mapped on to the original ECG signal (prior to downsampling) by scanning within a window around the R-peaks (detected in downsampled signal).

3. RESULTS

The performance evaluation of above proposed R-peak detection algorithm was carried out by testing it on standard data of Fantasia database, MIT-BIH arrhythmia database and self-recorded ECG signals [9]. The detection efficiency was described in terms of sensitivity ($S_e$) and positive predictivity ($+P$), which in turn depends on number of false positive ($FP$), false negative ($FN$), and true positive ($TP$) as shown in equation (2) and (3).

$$S_e = \frac{TP}{TP+FN}$$

$$+P = \frac{TP}{TP+FP}$$

Where, $TP$ is the number of true positives (true detection), $FN$ is the number of false negatives (missed detection), and $FP$ is the number of false positives (erroneous detection). The sensitivity $S_e$ indicates the percentage of true beats that were correctly detected by the algorithm. The positive predictivity $+P$ indicate the percentage of beat detection which were in reality true beats. The algorithm was tested using different wavelet families in the wavelet packet decomposition tree, the best results were achieved with db2. The test results shown in this paper are based on db2. An overall sensitivity and positive predictivity of 100% was achieved for tested records of Fantasia database and self-recorded signals, whereas sensitivity of 99.94% and positive predictivity of 99.93% was achieved for records of MIT-BIH arrhythmia database tested with this proposed algorithm.

3.1 Test results of Fantasia database

The Fantasia database contains 40 signals, each of 120 minutes duration and sampled at 250 Hz. The algorithm was tested on ten records. Figure 6 and Figure 7 shows the detected R-peaks in record no. f2o01 and f2o05. Table 1 shows the test results of the algorithm on tested records of Fantasia database.

3.2 Test results of self-recorded signals

The lead-II ECG signals in 10 subjects at sampling frequency of 500 Hz were recorded using BIOPAC MP 100 system. Figure 8 shows the test results of the algorithm on subject S1 of the self-recorded ECG signals. Table 2 shows the test results of the algorithm on self-recorded signals.

3.3 Test results of MIT-BIH arrhythmia database

The MIT-BIH arrhythmia database contains 48 records in total, each of 30 minutes duration and sampled at 360 Hz. The R-peaks detection was tested on 20 records of MIT-BIH arrhythmia database. Figure 8, Figure 9 and Figure 10 shows the detected R-peaks in record no. 100, 112, and 231 respectively of the tested ECG signals. Table 3 shows the test results for all tested 20 records of MIT-BIH arrhythmia database.

4. DISCUSSIONS

The test results with proposed wavelet packet based R-peak detection algorithm has shown very high detection efficiency when tested on standard data of Fantasia database, MIT-BIH arrhythmia database and self-recorded database. For ECG records of Fantasia database and self-recorded database, the algorithm has shown 100% detection efficiency. However the algorithm achieves an overall sensitivity of 99.94% and a positive predictivity of 99.93% on the MIT-BIH arrhythmia database as can be seen in Table 3.

Table 1 R-peak detection efficiency evaluation on Fantasia database

<table>
<thead>
<tr>
<th>Record No.</th>
<th>Actual no. of beats</th>
<th>No. of detected beats</th>
<th>TP</th>
<th>FP</th>
<th>FN</th>
<th>$S_e$</th>
<th>$+P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1o01</td>
<td>392</td>
<td>392</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f1o02</td>
<td>303</td>
<td>303</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f1o04</td>
<td>250</td>
<td>250</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o01</td>
<td>339</td>
<td>339</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o03</td>
<td>301</td>
<td>301</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o04</td>
<td>302</td>
<td>302</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o05</td>
<td>347</td>
<td>347</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o06</td>
<td>239</td>
<td>239</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o07</td>
<td>254</td>
<td>254</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>f2o08</td>
<td>320</td>
<td>320</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>2747</td>
<td>2747</td>
<td>274</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Fig 7: Detected R-peaks in self-recorded signal S1

Table 2 R-peak detection efficiency evaluation on self-recorded signals

<table>
<thead>
<tr>
<th>Subject</th>
<th>Actual No of beats</th>
<th>No of detected beats</th>
<th>TP</th>
<th>FP</th>
<th>FN</th>
<th>SE</th>
<th>+P</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>258</td>
<td>258</td>
<td>258</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S2</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S3</td>
<td>249</td>
<td>249</td>
<td>249</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S4</td>
<td>317</td>
<td>317</td>
<td>317</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S5</td>
<td>281</td>
<td>281</td>
<td>281</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S6</td>
<td>254</td>
<td>254</td>
<td>254</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S7</td>
<td>259</td>
<td>259</td>
<td>259</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S8</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S9</td>
<td>333</td>
<td>333</td>
<td>333</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S10</td>
<td>230</td>
<td>230</td>
<td>230</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2625</strong></td>
<td><strong>2625</strong></td>
<td><strong>2625</strong></td>
<td>0</td>
<td>0</td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

But for many records such as record no. 100, 103, 112, 115, etc. it has was able to correctly locate all the R-peaks on actual positions. The Figure 8 and Figure 9 show the small part of signal for record no. 100 and 112. Thus sensitivity and positive predictivity was found to be 100% for these records. In some of the records, the algorithm fails to detect few beats or detects

Table 3 R-peak detection efficiency evaluation on MIT-BIH arrhythmia database

<table>
<thead>
<tr>
<th>Record no.</th>
<th>Actual no. of beats</th>
<th>No. of detected beats</th>
<th>TP</th>
<th>FP</th>
<th>FN</th>
<th>SE</th>
<th>+P</th>
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<tbody>
<tr>
<td>100</td>
<td>2273</td>
<td>2273</td>
<td>2273</td>
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<td>0</td>
<td>100.0</td>
<td>100.0</td>
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<tr>
<td>101</td>
<td>1865</td>
<td>1865</td>
<td>1863</td>
<td>2</td>
<td>2</td>
<td>99.89</td>
<td>99.89</td>
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<tr>
<td>102</td>
<td>2187</td>
<td>2187</td>
<td>2186</td>
<td>1</td>
<td>1</td>
<td>99.95</td>
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</tr>
<tr>
<td>103</td>
<td>2084</td>
<td>2084</td>
<td>2084</td>
<td>0</td>
<td>0</td>
<td>100.0</td>
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<tr>
<td>107</td>
<td>2137</td>
<td>2140</td>
<td>2137</td>
<td>3</td>
<td>0</td>
<td>100.0</td>
<td>99.85</td>
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<tr>
<td>112</td>
<td>2539</td>
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<td>115</td>
<td>1953</td>
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<td>118</td>
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<tr>
<td>122</td>
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<td>0</td>
<td>0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>123</td>
<td>1518</td>
<td>1518</td>
<td>1517</td>
<td>1</td>
<td>1</td>
<td>99.93</td>
<td>99.93</td>
</tr>
</tbody>
</table>
Future work may be extended towards studying the algorithm performance with other wavelet families. Even optimal frequency bands may be worked upon to enhance the peak detection efficiency. This proposed R-peak detection algorithm will result into highly accurate heart rate variability signal, which can have potential to enhance the accuracy in cardiac health prognosis.

6. REFERENCES


| 124 | 1619 | 1619 | 1615 | 4 | 4 | 99.75 | 99.75 |
| 205 | 2656 | 2657 | 2652 | 5 | 4 | 99.82 | 99.79 |
| 209 | 3006 | 3011 | 3006 | 5 | 0 | 100.0 | 99.83 |
| 212 | 2748 | 2749 | 2748 | 1 | 0 | 100.0 | 99.96 |
| 215 | 3363 | 3366 | 3363 | 3 | 0 | 100.0 | 99.91 |
| 219 | 2154 | 2153 | 2152 | 1 | 2 | 99.91 | 99.95 |
| 220 | 2048 | 2047 | 2047 | 0 | 1 | 99.95 | 100.0 |
| 231 | 1573 | 1571 | 1571 | 0 | 2 | 99.87 | 100.0 |
| 234 | 2753 | 2746 | 2746 | 0 | 7 | 99.74 | 100.0 |
| Total | 4509 | 4509 | 4506 | 33 | 27 | 99.94 | 99.93 |