GPS Accuracy in Urban Environments Using Post-Processed CORS Data

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Presentation Topics

- Post Processing Overview
- Test Results in Obstructed Environments
- Next steps – Looking Ahead to 2020
- Summary
National Positioning, Navigation, and Timing (PNT) Architecture Study

- In 2006 the Assistant Secretary of Defense for Networks and Information Integration (ASD/NII) and the Under Secretary of Transportation for Policy (UST/P) sponsored a National Positioning, Navigation, and Timing (PNT) Architecture Study to “provide more effective and efficient PNT capabilities focused on the 2025 time frame...”

- Several NOAA organizations, including the National Geodetic Survey (NGS), participated on the Architecture Development Team (ADT) and are, additionally, members of the Architecture Transition Team (ATT).

- The PNT Joint Capabilities Document (JCD) identified a number of validated gaps in capability which are projected to exist in the 2025 timeframe.

- The team identified 7 gaps and the key gap related to this presentation was:
- **Assured and real-time PNT in physically impeded environments.**
- The large data set gathered (approximately 106 Million data points) during the Census Address Canvassing can provide a very good assessment of what are the PNT capabilities of GPS in a partially impeded physical environment today.
Address Canvassing

- The Census Bureau used Hand Held Computers (HHCs) to capture GPS structure points for every housing unit during its Address Canvassing field operation.
  - The Address Canvassing operation supported the 2010 Census.
  - Address Canvassing is the first nationwide collection of housing unit structure points using GPS technology to be conducted by the Census Bureau.
  - Field collection occurred in spring 2009.
  - The Hand Held Computer has Wide Area Augmentation System (WAAS) capability to increase point position accuracy to 3 meters or less in an unobstructed environment.
NGS Post Processing of Census Data

- The Hand Held Computer was modified to store all visible satellite pseudoranges when a GPS mapspot was recorded by an Address Canvasser.
- This data was post processed using the nearest CORS station to provide a more accurate coordinate for the structure address.
- Accuracy is three meters or less using a CORS station at a maximum distance of 200 Kms.
- Post Processing extends the increased accuracy to all data points when the WAAS satellite is blocked.
Wilson, David L. GPS WAAS Accuracy.
http://users.erols.com/dlwilson/gpswaas.htm
Present CORS Network
Post-Processed Position Errors at NGS MARK F304
(Melbourne, FL)
re CORS BRTW Ref. Station @ 120 Km.
HHC WAAS Position Errors at NGS F304 (Melbourne, FL) Ref. Mark

- Census 95% Radial Error (3 m.)
- HHC WAAS Position Errors (2998 data points)
- HHC WAAS 95% Radial Error (1.69 m.)
HHC WAAS Post-Processed Position Errors at NGS Mark F304 (Melbourne, FL) re CORS BRTW Reference Station @ 120 Km.
# GPS Post-Processed & WAAS Accuracy at Melbourne, FL NGS Reference Marks

<table>
<thead>
<tr>
<th>Description</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Processed with 120 Km Ref. Station</td>
<td>1.55 m. (95%) @ F304</td>
</tr>
<tr>
<td>WAAS @ F304</td>
<td>1.69 m. (95%)</td>
</tr>
<tr>
<td>WAAS @ 5062 (THRON)</td>
<td>1.50 m. (95%)</td>
</tr>
<tr>
<td>WAAS Post-Processed with 120 Km Ref. Station</td>
<td>1.70 m. (95%) @ F304</td>
</tr>
</tbody>
</table>
**Table 1 Post-Processed Results**

**Church Parking Lot**

<table>
<thead>
<tr>
<th>RMS (m.)</th>
<th>WAAS? Yes=2 No=1</th>
<th>East Error (m.)</th>
<th>North Error (m.)</th>
<th>Time HH/MM/SS</th>
<th>Data Point Desig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.6</td>
<td>2</td>
<td>-10.29</td>
<td>8.66</td>
<td>140851</td>
<td>T2</td>
</tr>
<tr>
<td>2.6</td>
<td>2</td>
<td>-0.61</td>
<td>-1.14</td>
<td>141027</td>
<td>T4</td>
</tr>
<tr>
<td>9.9</td>
<td>1</td>
<td>-2.04</td>
<td>1.04</td>
<td>141107</td>
<td>T5</td>
</tr>
<tr>
<td>5.6</td>
<td>1</td>
<td>-1.91</td>
<td>-0.52</td>
<td>141149</td>
<td>T6</td>
</tr>
<tr>
<td>3.2</td>
<td>1</td>
<td>-1.57</td>
<td>-0.85</td>
<td>141237</td>
<td>T7</td>
</tr>
<tr>
<td>2.7</td>
<td>2</td>
<td>-0.47</td>
<td>-0.66</td>
<td>141812</td>
<td>T14</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-1.38</td>
<td>1.42</td>
<td>141856</td>
<td>T15</td>
</tr>
<tr>
<td>2.4</td>
<td>2</td>
<td>0.01</td>
<td>-3.63</td>
<td>141938</td>
<td>T16</td>
</tr>
<tr>
<td>10.2</td>
<td>2</td>
<td>7.94</td>
<td>-10.5</td>
<td>142101</td>
<td>T18</td>
</tr>
<tr>
<td>8.8</td>
<td>2</td>
<td>-7.21</td>
<td>7.47</td>
<td>142146</td>
<td>T19</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>0.61</td>
<td>-4.08</td>
<td>142235</td>
<td>T20</td>
</tr>
<tr>
<td>1.2</td>
<td>2</td>
<td>0.72</td>
<td>0.27</td>
<td>142317</td>
<td>T21</td>
</tr>
</tbody>
</table>

About 60% of post-processed data within 3 m. of a parking lot reference stripe in a good GPS signal environment.

Data taken 04/13/2009 using CORS station “gode” located at the NASA Goddard Space Flight Center.
### Table 2 Post-Processed “Church II” Results

<table>
<thead>
<tr>
<th>RMS (m.)</th>
<th>WAAS?</th>
<th>East Error (m.)</th>
<th>North Error (m.)</th>
<th>Time HH/MM/SS</th>
<th>Data Point Desig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>1</td>
<td>2.09</td>
<td>-1.74</td>
<td>143343</td>
<td>H1</td>
</tr>
<tr>
<td>32.5</td>
<td>1</td>
<td>2.58</td>
<td>-0.46</td>
<td>143514</td>
<td>H2</td>
</tr>
<tr>
<td>35.7</td>
<td>1</td>
<td>5.82</td>
<td>-5.5</td>
<td>143914</td>
<td>H5</td>
</tr>
<tr>
<td>18.2</td>
<td>1</td>
<td>1.85</td>
<td>-0.78</td>
<td>144015</td>
<td>H6</td>
</tr>
<tr>
<td>12.8</td>
<td>1</td>
<td>4.54</td>
<td>1.66</td>
<td>144111</td>
<td>H7</td>
</tr>
<tr>
<td>2.1</td>
<td>1</td>
<td>-3.5</td>
<td>5.3</td>
<td>144214</td>
<td>H8</td>
</tr>
<tr>
<td>3.5</td>
<td>1</td>
<td>2.19</td>
<td>-3.4</td>
<td>144325</td>
<td>H9</td>
</tr>
<tr>
<td>13.1</td>
<td>1</td>
<td>-8.23</td>
<td>3.56</td>
<td>144431</td>
<td>H10</td>
</tr>
<tr>
<td>13.6</td>
<td>1</td>
<td>-3.9</td>
<td>1.33</td>
<td>144600</td>
<td>H11</td>
</tr>
<tr>
<td>16.2</td>
<td>1</td>
<td>-0.1</td>
<td>0.47</td>
<td>144709</td>
<td>H12</td>
</tr>
<tr>
<td>6.6</td>
<td>1</td>
<td>-9.91</td>
<td>7.3</td>
<td>144809</td>
<td>H13</td>
</tr>
<tr>
<td>47.9</td>
<td>1</td>
<td>-4.59</td>
<td>1.82</td>
<td>144908</td>
<td>H14</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>-22.17</td>
<td>6.93</td>
<td>145108</td>
<td>H15</td>
</tr>
<tr>
<td>20.7</td>
<td>1</td>
<td>-15.84</td>
<td>6.51</td>
<td>145206</td>
<td>H16</td>
</tr>
</tbody>
</table>

About 30% of Post Processed Data Within 3 m. of Map Spot

About 60% of Data Within 5 m. of Map Spot in a partially obstructed environment.
Maryland Test Results November 2008

- First Data Set from Harris with SiRF Chip Set Message ID-28 Enabled
- 5 Test Address Canvassing Residential Areas, a Parking Lot and a Baseball Park
- 400 Data Points Post Processed; Post Processed Points used as Data Quality Indicator for Map Spot Data
- Parking Lot - 2 of 3 Post Processed Points within 3 Meters. All Map Spots Were WAAS Corrected
Maryland Residential Area Test Results 11/20 & 11/21/2008

- 11/20 – 16% of Map Spot Data Within 3 m. of Post Processed Data; 36% Within 5 m.

- 11/20 - WAAS Corrections on 25% of Data (200 Data Points)

- 11/21 – 14% of Map Spot Data Within 3 m. of Post Processed Data; 31% Within 5 m.

- 11/21 - WAAS Corrections on 18% of Data (196 Data Points)
### Address Canvassing Results from NGS Post-Processing Software

<table>
<thead>
<tr>
<th>TOTAL OUTPUT</th>
<th>75,715,492</th>
<th>% of TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptable Solutions / Data Meets Census Requirements</td>
<td>60,454,515</td>
<td>79.84%</td>
</tr>
<tr>
<td>Unacceptable Solutions / Data Requirements Not Met</td>
<td>12,449,324</td>
<td>16.44%</td>
</tr>
<tr>
<td>No Solution for Raw GPS or Post Processed Data</td>
<td>2,811,653</td>
<td>3.71%</td>
</tr>
</tbody>
</table>
## POTENTIAL SOLUTIONS

<table>
<thead>
<tr>
<th>DISTANCE (m) RAW to PP</th>
<th>Number of MSPs</th>
<th>% of MSPs</th>
<th>AVG DISTANCE RAW to PP</th>
<th>AVG RMS RAW to PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5.0</td>
<td>32,661,843</td>
<td>54.03%</td>
<td>2.70</td>
<td>1.70</td>
</tr>
<tr>
<td>5.0 - 10.0</td>
<td>16,269,070</td>
<td>26.91%</td>
<td>7.06</td>
<td>2.02</td>
</tr>
<tr>
<td>10.0 - 15.0</td>
<td>6,036,542</td>
<td>9.99%</td>
<td>12.13</td>
<td>2.18</td>
</tr>
<tr>
<td>15.0 - 20.0</td>
<td>2,620,523</td>
<td>4.33%</td>
<td>17.18</td>
<td>2.25</td>
</tr>
<tr>
<td>Greater than 20.0</td>
<td>2,866,537</td>
<td>4.74%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Analysis of the Effects of Surface Features on the Accuracy of Post-Processed Structure Points in the 2010 Address Canvassing

- Objective: To assess the effects of selected surface features on the accuracy of the GPS Post-Processed data.
- General surface conditions were selected based on two criteria:
  - Tree canopy cover
  - Development intensity
Research methodology

- MAF Structure Points (MSPs) and related data elements will be identified and extracted from the MAF/TIGER database (MTDB).
- From the data extract, partial county-level test sites will be selected and output to shapefile format.
- Analysts will visually inspect and categorize surface conditions for selected variables.
- The output from these processes will be provided to the NGS for analysis.
Pre-Processing Tasks

- Selection of test site locations
- Creation of shapefiles
- Creation of ArcGIS projects
  - data extract will be plotted in ArcGIS and reviewed for selection of test areas
  - areas chosen for review will include urban core, suburban residential and rural development in a variety of geographic locations
- Imagery assessment
Canopy Attribute

- **I_CANOPY** attribute
  - **L** – Low – less than 30% of the surrounding 50 m – urban center, new suburban
  - **M** – Med – greater than 30% and less than 60% of the surrounding 50 m – older suburbs, some rural
  - **H** – High – greater than 60% of the surrounding 50 m – rural, some suburban (rarely)
Man-made Development Attribute

- I_DV_INT attribute
  - L – Low Density, low density suburban, single family detached (large lots), rural
  - M – Med Density, higher density suburban (small lots), townhouses, some multi-unit structures
  - H – High Density, large towers, large apartment buildings, urban core

- In some instances it may be useful to extend the review to the 125m square (Figure 1), in order to assess development intensity.
Low Canopy Cover

<table>
<thead>
<tr>
<th>Low Development Density</th>
<th>Med Development Density</th>
<th>High Development Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Low Canopy" /></td>
<td><img src="image2" alt="Medium Canopy" /></td>
<td><img src="image3" alt="High Canopy" /></td>
</tr>
</tbody>
</table>
**Medium Canopy Cover**

<table>
<thead>
<tr>
<th>Low Development Density</th>
<th>Med Development Density</th>
<th>High Development Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Test Data Subsets

- 11 test areas
  - around 3000 MSPs (MAF Structure Points) per test area
- 7 test areas, with about 21,000 MSPs
  - part of the core review
- 33,110 MSP’s reviewed
### WAAS Percentages re Canopy Cover and Level of Development / All Data Sets

<table>
<thead>
<tr>
<th>I_CANOPY</th>
<th>I_DV_INT</th>
<th>WAAS</th>
<th>Number</th>
<th>% of All</th>
<th>Category Total</th>
<th>% of Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>L</td>
<td>GPS Only</td>
<td>372</td>
<td>1.12%</td>
<td>518</td>
<td>71.81%</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>WAAS</td>
<td>146</td>
<td>0.44%</td>
<td></td>
<td>28.19%</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>GPS Only</td>
<td>144</td>
<td>0.43%</td>
<td>196</td>
<td>73.47%</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>WAAS</td>
<td>52</td>
<td>0.16%</td>
<td></td>
<td>26.53%</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>GPS Only</td>
<td>2337</td>
<td>7.06%</td>
<td>4553</td>
<td>51.33%</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>WAAS</td>
<td>2216</td>
<td>6.69%</td>
<td></td>
<td>48.67%</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>GPS Only</td>
<td>1883</td>
<td>5.69%</td>
<td>3328</td>
<td>56.58%</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>WAAS</td>
<td>1445</td>
<td>4.36%</td>
<td></td>
<td>43.42%</td>
</tr>
<tr>
<td>L</td>
<td>M</td>
<td>GPS Only</td>
<td>8894</td>
<td>26.86%</td>
<td>20334</td>
<td>43.74%</td>
</tr>
<tr>
<td>L</td>
<td>M</td>
<td>WAAS</td>
<td>11440</td>
<td>34.55%</td>
<td></td>
<td>56.26%</td>
</tr>
<tr>
<td>M</td>
<td>H</td>
<td>GPS Only</td>
<td>101</td>
<td>0.31%</td>
<td>208</td>
<td>48.56%</td>
</tr>
<tr>
<td>M</td>
<td>H</td>
<td>WAAS</td>
<td>107</td>
<td>0.32%</td>
<td></td>
<td>51.44%</td>
</tr>
<tr>
<td>M</td>
<td>L</td>
<td>GPS Only</td>
<td>1082</td>
<td>3.27%</td>
<td>1567</td>
<td>69.05%</td>
</tr>
<tr>
<td>M</td>
<td>L</td>
<td>WAAS</td>
<td>485</td>
<td>1.46%</td>
<td></td>
<td>30.95%</td>
</tr>
<tr>
<td>M</td>
<td>M</td>
<td>GPS Only</td>
<td>1397</td>
<td>4.22%</td>
<td>2406</td>
<td>58.06%</td>
</tr>
<tr>
<td>M</td>
<td>M</td>
<td>WAAS</td>
<td>1009</td>
<td>3.05%</td>
<td></td>
<td>41.94%</td>
</tr>
</tbody>
</table>
### WAAS Percentages and Accuracy for Canopy Cover and Level of Development for Larger Data Sets

<table>
<thead>
<tr>
<th>Canopy Cover</th>
<th>Development Density</th>
<th>Relative Accuracy (95%)</th>
<th>Category Total</th>
<th>WAAS % of Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>23.9 m.</td>
<td>3328</td>
<td>43.4%</td>
</tr>
<tr>
<td>Low</td>
<td>Medium</td>
<td>22.5 m.</td>
<td>20334</td>
<td>56.2%</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>26.3 m.</td>
<td>4553</td>
<td>48.7%</td>
</tr>
<tr>
<td>All</td>
<td>All</td>
<td>24.4 m.</td>
<td>33110</td>
<td>51.0%</td>
</tr>
</tbody>
</table>
Summary Test Conclusions

- NGS Post-Processing accuracy using CORS Reference stations was less than three meters (95%) in unobstructed environments.
- The 95% relative accuracy estimate for the 60 million data points processed during the Address Canvassing was 15 – 20 m.
- Post-processed coordinates minus map spot coordinates in partially obstructed environments range from 22.5 m. to 26.3 m. @ 95% accuracy in subsets analyzed. Fifty four percent (54% - 32.6 million points) of all data sets processed were between 0-5 m.
Next Steps

• What future methodologies can be used to improve the accuracy in partially obstructed environments for the 2020 Census or other future applications in the urban environment?
• Multiple GNSS Constellations

• Miniature Geodetic Type Antennas in Hand Held GPS Receivers

• Automated Spatial Analysis
Study Conditions

- Population data obtained from the Center for International Earth Science Information Network at Columbia University.
- Cities exceeding a half million people were selected.
- Total of 5173 sites used to produce separate statistics in open sky and urban sites.
- Mask angles of 15 and 30 degrees used in addition to multipath models in urban sites.
- GPS and GALILEO (Walker 27/3/1) constellations of 24 and 27 satellites respectively were considered.
- Future GPS-III, Galileo and combined GPS-III/Galileo signals considered.

Half-Sky Study Global Statistic of Mean HPE for Average Solar Cycle

<table>
<thead>
<tr>
<th>System</th>
<th>SF: BOC(1,1)</th>
<th>SF: MBOC</th>
<th>DF: MBOC-BPSK10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%ge pdop ≤ 10 &amp; nsat ≤ 4</td>
<td>63.16%</td>
<td>63.16%</td>
<td>63.16%</td>
</tr>
<tr>
<td>mean</td>
<td>9.39</td>
<td>7.68</td>
<td>4.08</td>
</tr>
<tr>
<td>stdev</td>
<td>1.94</td>
<td>2.08</td>
<td>0.60</td>
</tr>
<tr>
<td>RMS</td>
<td>9.59</td>
<td>7.96</td>
<td>4.12</td>
</tr>
<tr>
<td>Median</td>
<td>9.33</td>
<td>7.77</td>
<td>3.96</td>
</tr>
<tr>
<td>95th</td>
<td>12.59</td>
<td>11.03</td>
<td>5.11</td>
</tr>
<tr>
<td><strong>Galileo</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%ge pdop ≤ 10 &amp; nsat ≤ 4</td>
<td>78.57%</td>
<td>78.57%</td>
<td>78.57%</td>
</tr>
<tr>
<td>mean</td>
<td>10.48</td>
<td>9.09</td>
<td>6.11</td>
</tr>
<tr>
<td>stdev</td>
<td>2.18</td>
<td>2.17</td>
<td>1.02</td>
</tr>
<tr>
<td>RMS</td>
<td>10.70</td>
<td>9.35</td>
<td>6.20</td>
</tr>
<tr>
<td>Median</td>
<td>10.42</td>
<td>9.01</td>
<td>6.25</td>
</tr>
<tr>
<td>95th</td>
<td>14.17</td>
<td>12.81</td>
<td>7.47</td>
</tr>
<tr>
<td><strong>GPS &amp; Galileo</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%ge pdop ≤ 10 &amp; nsat ≤ 4</td>
<td>98.92%</td>
<td>98.92%</td>
<td>98.92%</td>
</tr>
<tr>
<td>mean</td>
<td>6.11</td>
<td>5.28</td>
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## Urban Global Study (30 Deg.)
### Global Statistics of HPE

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## Census Accuracy re EU-US Studies

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<th>2 sigma (95%)</th>
<th>GPS and Galileo 2 sigma (95%)</th>
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<td>GPS L1 C/A – Post Processed</td>
<td>15 - 20 m.</td>
<td>10.5 m.</td>
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<td>12.6 – 14.2 m.</td>
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<td>Urban 30 deg. Mask / GPS III-F or Galileo</td>
<td>12.7 – 15.9 m.</td>
<td>8.0 m.</td>
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Multipath Mitigation Antenna Research

- Small Business Innovation Research (SBIR) Grants awarded to Toyon Research Corporation
  - Phase I and Phase II Grants

- Prototype Antenna delivered to NGS in August 2008
  - Tests conducted near a lighthouse in South Carolina
  - Objective is to evaluate multipath mitigation at high elevation angles
  - Compare results with choke ring antenna
Toyon Antenna Patterns (RHCP & LHCP)
North & East Errors / Stand Alone Point Positioning
Post-Processed Accuracy Using a Multipath Mitigation Antenna about 3.5 m. from Residence

Toyon Antenna Configuration #1 (No Radome) in a Multipath Environment Goleta CA, June 23, 2008

- Toyon Post Processed Position Errors (18220 Data Points)
- Post Processed 95% Radial Error (2.72 m.)
- Average Position Coordinate (All Data)
Airborne Lidar Data Used with a Filter to Remove Canopy Cover

Precise Geodetic Infrastructure: National Requirements for a Shared Resource Committee on the National Requirements for Precision Geodetic Infrastructure; Committee on Seismology and Geodynamics; National Research Council /ISBN 978-0-309-15811-4, p. 60.
Summary of Next Steps

- Use of Multiple GNSS Constellations
  - Increases Accuracy by approximately 40%

- Use of Multipath Mitigation Antennas in Hand Held GPS receivers
  - antenna increases accuracy in an obstructed environment from 5 m. to less than 3 m. with post processing

- Automated Spatial Analysis provides “ground truth” data to evaluate GPS accuracy from imagery
  - Use of Lidar allows removal of canopy cover using filtering