Spacecraft Precision Attitude Determination using U V F Measurements

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Abstract: This paper proposes a novel approach of a precision attitude determination algorithm using UVF (Unit Vector Filter) measurements. The proposed method is superior to the conventional QUEST measurements based approaches because the estimation performance can be greatly enhanced by selecting brighter stars having better noise characteristics. The performance comparison with QUEST measurements is made to verify the usefulness of the proposed algorithm.

Keywords: Precision Attitude Determination, UVF (Unit Vector Filter) Measurement, QUEST Measurement

1. INTRODUCTION

Recent development in remote sensing technology has brought out the need of much more accurate attitude information during the imaging period for the provision of value-added image products. In general, the real-time on-board estimation of a spacecraft attitude does not satisfy the accuracy requirement because a linearized attitude dynamics must be adopted due to the limited computational capability of the on-board processor and the lack of ancillary information. The restitution of accurate attitude information is, therefore, generally carried out at ground stations and it is called the precise attitude determination (PAD) algorithm.

The precise attitude determination with the accuracy of tens of arc-seconds (resulting in several tens of meters geo-location accuracy) is still challenging due to several factors; e.g. the high-frequency variation and perturbation of the attitude dynamics as well as the noise and stability characteristics of attitude sensors currently available. Therefore, the improvement of attitude determination accuracy is essential in order to achieve a comparable amount of ultimate geo-location uncertainty to the orbit determination.

The development of a PAD algorithm and software includes many technological aspects such as the precise modeling of attitude dynamics and sensor characteristics, the implementation of an attitude estimator such as a batch least square estimator, an extended Kalman filter or an unscented Kalman filter, and the analytic and/or experimental determination of noise parameters. Among them, the sensor output characteristics have direct impact on the estimation performance regardless of the estimation method or the dynamic model of the spacecraft.

Two types of sensor data are generally used for the attitude estimation: gyro output providing the inertial rate information of a spacecraft attitude does not satisfy the uncertainty to the orbit determination. The satellite's attitude information is, therefore, defined as the on-board star catalog coordinate system using on-board estimation algorithm. Thus the user can simply use the estimated attitude information as the coordinate system. Gyro output providing the inertial rate information of a spacecraft attitude does not satisfy the uncertainty to the orbit determination.

The definitions of coordinate systems are identical with [1]. The satellite is assumed to have a main imaging payload of a push-broom type. The optical bench frame (OBF) of the satellite is thought to be the mechanical body frame. The satellite's attitude information is, therefore, defined as the OBF with respect to an inertial celestial reference frame (CRF) such as J2000 coordinate. Let s denote the roll, pitch, and yaw rotational angles as \( \phi, \theta, \) and \( \psi \), respectively. Then the 3-2-1 Euler rotational matrix from CRF to OBF is expressed as:

\[
\begin{bmatrix}
1 & -\psi & \theta - \phi \theta \\
\psi & 1 & \psi \theta + \phi \\
-\theta & \psi \phi - \phi \theta & 1
\end{bmatrix}
\]

Another expression of the rotational matrix of \( (1) \) using the attitude quaternion is expressed as [2].

\[
q(q) = \begin{bmatrix}
2(1_1^2 + 1_2^2 - 1_3^2 - 1_4^2) \\
2(1_1 1_2 - 1_3 1_4) \\
2(1_1 1_3 + 1_2 1_4) \\
2(1_1 1_3 - 1_2 1_4)
\end{bmatrix}
\]


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Two star trackers are mounted on the satellite with different bore-sight directions to compensate the poor angular accuracy around the bore-sight axes. The two star tracker coordinates are denoted as SCF1 and SCF2, respectively, and the rotational matrix from OBF (as the body frame) to SCF1 and SCF2 are specified as:

\[
\begin{bmatrix}
-0.53908705 & 0.3508722 & -0.76604444 \\
-0.54463904 & -0.83867057 & 0 \\
-0.64245893 & 0.41721771 & 0.64278761 \\
0.53908705 & 0.3508722 & -0.76604444 \\
-0.54463904 & 0.83867057 & 0 \\
0.64245893 & 0.41721771 & 0.64278761 
\end{bmatrix}
\]  

(3)

The rotation between OBF and SCF can also be expressed as quaternion as:

\[
\vec{q}^1 = \vec{q}^2 \Rightarrow \vec{q}^1 = \begin{bmatrix} -0.40521473 & 0.12003007 & 0.86898579 & 0.25740532 \end{bmatrix} \]

(4)

The rotation between OBF and SCF can also be expressed as quaternion as:

\[
\begin{bmatrix}
-0.53908705 & 0.3508722 & -0.76604444 \\
-0.54463904 & -0.83867057 & 0 \\
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\begin{bmatrix}
-0.40521473 & 0.12003007 & 0.86898579 & 0.25740532 \\
0.12003007 & -0.86898579 & 0.25740532 & 0.86898579 \\
0.12003007 & 0.86898579 & -0.25740532 & 0.86898579 \\
-0.40521473 & -0.12003007 & 0.25740532 & 0.86898579 
\end{bmatrix}
\]

(4)

The satellite has an inertial reference unit (IRU) measuring the satellite’s body rate. The IRU has four sets of gyros, providing a full 3-axis inertial rate measurement with a redundancy. The relation between the IRU assembly coordinate system, or GCF (gyro coordinate system), and the four gyro measurement directions is specified as:

\[
\vec{\omega} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{\omega_x}{\sqrt{2}} - \frac{\omega_y}{\sqrt{2}} - \frac{\omega_z}{\sqrt{2}} \\ -\frac{\omega_x}{\sqrt{2}} + \frac{\omega_y}{\sqrt{2}} - \frac{\omega_z}{\sqrt{2}} \\
-\frac{\omega_x}{\sqrt{2}} - \frac{\omega_y}{\sqrt{2}} + \frac{\omega_z}{\sqrt{2}} \\
-\frac{\omega_x}{\sqrt{2}} + \frac{\omega_y}{\sqrt{2}} + \frac{\omega_z}{\sqrt{2}} \\ \frac{\omega_x}{\sqrt{2}} + \frac{\omega_y}{\sqrt{2}} + \frac{\omega_z}{\sqrt{2}} \end{bmatrix}
\]

(5)

The mounting direction of the IRU with respect to OBF is specified as:

\[
\vec{g} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
\]

(6)

3. E UATIONS OF MOTION

The linearized 6-state equation of motion for attitude determination is expressed as [3]

\[
\frac{d}{dt} \begin{bmatrix} \delta \\ \vec{b} \end{bmatrix} = \begin{bmatrix} -[\alpha \vec{x}] & \begin{bmatrix} 0 & I & 0 \\ 0 & 0 & I \\ 0 & I & 0 \end{bmatrix} \end{bmatrix} \begin{bmatrix} \delta \\ \vec{b} \end{bmatrix} + \begin{bmatrix} 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \vec{\eta}
\]

(7)

where \([\alpha \vec{x}]\) is the matrix expressing the vector cross product and defined as:

\[
[\alpha \vec{x}] = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}
\]

(8)

\[\vec{b}\] is the vector part of the quaternion error \(\delta = \vec{q} \otimes \vec{q}^*\) and \(\vec{q}^*\) is the conjugate quaternion of \(\vec{q}\) having the following characteristics:

\[
\vec{\delta} = \vec{q} \otimes \vec{q}^* = [0, 0, 0, 1]^T
\]

(9)

The conjugate quaternion expresses the inverse rotation of the original quaternion. \(\eta, \eta^*\) are the rate white noise and rate random walk noise, respectively. They are mutually independent white Gaussian random processes having the following statistical characteristics:

\[
\begin{bmatrix} \eta \\ \eta^* \end{bmatrix} = \sigma_{\omega} \begin{bmatrix} I_3 \\ I_3 \end{bmatrix}, \quad \begin{bmatrix} \eta^* \\ \eta \end{bmatrix} = \sigma_{\omega}^* \begin{bmatrix} I_3 \\ I_3 \end{bmatrix}
\]

(10)

The gyro bias error vector is defined as:

\[
\vec{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}
\]

(11)

is the estimated quaternion and \(\vec{\omega}\) is the body rate vector having the following relation with the drift bias vector

\[
\vec{\omega} = \vec{\omega}_b = \vec{b} + \vec{\omega}
\]

(12)

where \(\vec{\omega}_b\) is the body rate vector measured by IRU.

The 6-state equation of motion shall now be extended to include absolute GCF misalignment and scale factor error [4] by the following assumptions:

1. The GCF misalignment vector is defined as the difference between ground measured mounting direction, \(\vec{g}\), and the actual in-orbit mounting direction, \(\vec{g}_o\), as

\[
\vec{g}_m = \vec{g}_o \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} = \vec{g}_o \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
\]

(13)

2. The four gyros mounted in IRU have only diagonal scale factor errors and the scale factor error matrix is thus defined as the following diagonal matrix:

\[
\begin{bmatrix} \lambda_x & 0 & 0 \\ 0 & \lambda_y & 0 \\ 0 & 0 & \lambda_z \end{bmatrix}
\]

(14)

3. The IRU contains rate integration gyros and thus the gyro output is the accumulated rate information.

Then the gyro output vector is expressed as

\[
\vec{v} = \begin{bmatrix} \vec{v}_a \\ \vec{v}_r \end{bmatrix} = \begin{bmatrix} I + \Lambda \end{bmatrix}_o \begin{bmatrix} \vec{v}_a \\ \vec{v}_r \end{bmatrix} - \begin{bmatrix} \vec{b}_{\text{angle}} \\ \vec{b}_{\text{rate}} \end{bmatrix}
\]

(15)

where \(\vec{v}_a, \vec{v}_r\) are angle white noise and angle random walk noise, respectively and their standard deviations are \(\sigma_{\phi} \) and \(\sigma_{\phi'}\).

The extended equation of motion shall be derived from the body rate expression. Thus the angle output equation of (15)
shall be approximated as the following rate output equation by applying the finite difference method:

\[ \omega'_{s} = \frac{1}{(1 + \Lambda)} (1 - [\sigma_{G} \times]) \omega'_{s} - b_{s}^{t} - \eta'_{s} \]

(16)

The new noise characteristics are related with the angle output noise characteristics as:

\[ \hat{\eta}'_{s}, \eta''_{s} \stackrel{\gamma}{\rightarrow} \frac{2\sigma^{2}_{G}}{\Delta t} I_{4x4} \]

(17)

Now by assuming that the misalignment and scale factor error values are very small, (16) is expressed as

\[ \omega = \omega_{s} + \omega_{s}^{G} \]

(18)

where, \( \omega_{s}^{G} = \omega_{s} + \omega_{s}^{G} \). The last two terms of the above equation is expressed as

\[ \omega_{s}^{G} = \omega_{s}^{G} - \frac{1}{2} \sigma_{G} \times \delta_{G} \]

(20)

and thus the following relation is obtained.

\[ \omega'_{s} \approx \omega_{s}^{G} \]

(19)

The estimated body rate is obtained from (18) as

\[ \omega = \omega_{s}^{G} + \omega_{s}^{G} + \omega_{s}^{G} - \frac{1}{2} \sigma_{G} \times \delta_{G} \]

(21)

From the small angle rotation assumption, the quaternion error vector is related with the Euler angle error as

\[ \delta_{s} = \frac{1}{2} \delta \theta, \quad \delta_{s}^{\prime} = \frac{1}{2} (\omega - \omega) \]

(22)

where

\[ \Delta = \begin{bmatrix} \delta_{s} \\ \Delta \delta_{s} \\ \Delta \lambda_{s} \end{bmatrix}, \quad \eta = \begin{bmatrix} \hat{\eta}_{s} \\ \hat{\eta}_{s} \\ \hat{\eta}_{s} \end{bmatrix} \]

(23)

\[ G(t) = \begin{bmatrix} I_{4} \\ I_{4} \end{bmatrix} \]

(24)

\[ \hat{\eta}_{s}, \hat{\eta}_{s} \] are white Gaussian noise processes having their covariance matrices as \( \sigma^{2}_{G} I_{4}, \sigma^{2}_{G} I_{4} \), respectively.

4. STAR SENSOR MEASUREMENT MODELS

The star sensor misalignments do not affect satellite attitude and are only related with measurements. Thus there is no dynamic coupling between star tracker misalignments with (22) when they are augmented into the equation of motion.

The star sensor misalignment vector is calculated from the error quaternion between ground measured nominal mounting direction and the in-orbit mounting direction as:

\[ \omega = \omega_{s}^{G} \]

(25)

Two star sensors are assumed to be mounted on the spacecraft and thus two misalignment vectors are assumed to have the following statistical characteristics:

\[ \frac{1}{2} \delta_{1} = \hat{\eta}_{s}, \quad \frac{1}{2} \delta_{2} = \hat{\eta}_{s} \]

(26)

Now by defining the following error vectors

\[ \Delta \delta_{1} = \delta_{1} - \delta_{1}, \quad \Delta \delta_{2} = \delta_{2} - \delta_{2} \]

the augmented equation of motion is now expressed as

\[ \frac{d}{dt} \Delta = (t) \Delta + G(t) \eta \]

(27)

where

\[ \eta = \begin{bmatrix} \eta_{s} \\ \eta_{s} \\ \eta_{s} \end{bmatrix} \]

(28)

\[ G(t) = \begin{bmatrix} I_{4} \\ I_{4} \end{bmatrix} \]

(29)

The star sensor measurement equation is defined as the attitude of CCD array of the star sensor with respect to the inertial coordinate system(CRF) as:
Now we derive the measurement equation expression for the UVF measurement and QUEST measurement.

4.1 QUEST Measurement

The QUEST measurement is the quaternion determined by the on-board algorithm of the star sensor. The measurement residual is defined as

$$\hat{q}_{kk} = q_{kk} \odot \hat{q}_{kk}$$  \hspace{1cm} (27)

where $q_{kk}$ is the QUEST output of the star sensor and $\hat{q}_{kk}$ is the \textit{a priori} quaternion estimate obtained by integrating quaternion kinematics with the initial condition of $\hat{q}_{kk}$. Also, $\hat{q}_{kk}$ is the estimate of $\hat{q}_{kk}$ and is expressed as

$$\hat{q}_{kk} = q_{kk} \odot \hat{q}_{kk}$$  \hspace{1cm} (28)

Now (28) can be expressed as

$$\hat{q}_{kk} = q_{kk} \odot \hat{q}_{kk}$$  \hspace{1cm} (29)

The above expression is identical with the result of [4].

Now by ignoring the second order terms with respect to the state variables, the vector term of the QUEST measurement residual is obtained as:

$$\hat{z}_{kk} = 0 = k - k + n_k$$  \hspace{1cm} (33)

and $n_k$ is the measurement noise.

Now, by expressing the rotational matrix as the exponential matrix, (34) becomes

$$k = R \hat{v}_k$$

and $\hat{v}_k$ is the true unit vector in SCF and is related with the corresponding star unit vector in CRF, $\hat{v}_k$, as

$$\hat{v}_k = 0 \odot \hat{v}_k$$  \hspace{1cm} (34)

Then the measurement residual is expressed as

$$\hat{z}_{kk} = k = 0 = k + n_k$$  \hspace{1cm} (35)

Thus (33) is expressed as

$$\hat{z}_{kk} = 0 = k = 0 + n_k$$

The measurement sensitivity matrix is obtained as
5. A SIMULATION RESULT

The performance when using the UVF measurement for the precision attitude determination is compared with the case of using the QUEST measurement. Sensor output and dynamics simulation are based on the implementation method expressed in [1]. The applied estimation method is the extended Kalman filter (EKF).

5.1 6-State Estimation using EKF

The 6-state estimation performance using EKF based on the dynamic model of (7) is shown in Table 1, Table 2, Figure 1 and Figure 2. Three UVF vectors are used for the estimation using the UVF measurements. The stars are ordered by its magnitude and only the three brightest stars are used.

5.2 Full State Estimation using EKF

The estimation performance using EKF based on the full state dynamics of (26) is shown in Figure 3, Table 3 and Table 4.

As expected, the localization error using the UVF measurements is superior to the case of using the QUEST measurements. The mean star magnitude of the UVF measurements is about 2.5 which gives smaller NEA (noise equivalent angle) than the QUEST measurements.

![Figure 2 6-State Geo-location Error (EKF+UVF)](image)

![Figure 3 Full State Geo-location Error (EKF+QUEST)](image)

When the number of stars used for the UVF measurements are

<table>
<thead>
<tr>
<th>Geo-location Error (CE 0 22.13 m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>198.46</td>
<td>20.53</td>
<td>-273.87</td>
<td>-127.11</td>
</tr>
<tr>
<td>Y</td>
<td>25.24</td>
<td>23.01</td>
<td>-94.05</td>
<td>40.70</td>
</tr>
</tbody>
</table>

Pointing Accuracy (arcsec)

<table>
<thead>
<tr>
<th>Yaw</th>
<th>RMSE</th>
<th>STD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.63</td>
<td>3.46</td>
<td>13.22</td>
<td>19.69</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>14.97</td>
<td>13.50</td>
<td>25.89</td>
<td></td>
</tr>
<tr>
<td>Roll</td>
<td>57.17</td>
<td>6.13</td>
<td>80.04</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 6-State Estimation Performance (EKF+QUEST)

<table>
<thead>
<tr>
<th>Geo-location Error (CE 0 13.1 m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
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</thead>
<tbody>
<tr>
<td>X</td>
<td>99.08</td>
<td>42.36</td>
<td>-151.14</td>
<td>15.93</td>
</tr>
<tr>
<td>Y</td>
<td>29.95</td>
<td>16.70</td>
<td>-69.09</td>
<td>15.77</td>
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</table>

Pointing Accuracy (arcsec)

<table>
<thead>
<tr>
<th>Yaw</th>
<th>RMSE</th>
<th>STD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.84</td>
<td>10.74</td>
<td>-30.21</td>
<td>10.98</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>5.21</td>
<td>5.21</td>
<td>-13.22</td>
<td>11.17</td>
</tr>
<tr>
<td>Roll</td>
<td>30.23</td>
<td>10.37</td>
<td>6.08</td>
<td>44.27</td>
</tr>
</tbody>
</table>

Table 2 6-State Estimation Performance (EKF+UVF)

<table>
<thead>
<tr>
<th>Geo-location Error (CE 0 0 m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>47.50</td>
<td>20.10</td>
<td>-165.69</td>
<td>14.58</td>
</tr>
<tr>
<td>Yaw</td>
<td>11.66</td>
<td>4.29</td>
<td>-30.21</td>
<td>12.89</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.88</td>
<td>3.60</td>
<td>-13.22</td>
<td>11.17</td>
</tr>
<tr>
<td>Roll</td>
<td>14.86</td>
<td>5.60</td>
<td>-1.75</td>
<td>48.90</td>
</tr>
</tbody>
</table>

Pointing Accuracy (arcsec)

<table>
<thead>
<tr>
<th>Yaw</th>
<th>RMSE</th>
<th>STD</th>
<th>Min</th>
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</thead>
<tbody>
<tr>
<td>11.66</td>
<td>4.29</td>
<td>-27.07</td>
<td>2.93</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>3.88</td>
<td>3.60</td>
<td>-13.59</td>
<td>11.66</td>
</tr>
<tr>
<td>Roll</td>
<td>14.86</td>
<td>5.60</td>
<td>-7.5</td>
<td>48.90</td>
</tr>
</tbody>
</table>

Table 3 Full State Estimation Performance (EKF+QUEST)

<table>
<thead>
<tr>
<th>Geo-location Error (CE 0 2.30 m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>43.79</td>
<td>9.93</td>
<td>-129.46</td>
<td>-14.47</td>
</tr>
<tr>
<td>Yaw</td>
<td>27.82</td>
<td>11.49</td>
<td>-12.60</td>
<td>54.78</td>
</tr>
<tr>
<td>Pitch</td>
<td>6.97</td>
<td>2.16</td>
<td>-12.78</td>
<td>12.89</td>
</tr>
<tr>
<td>Roll</td>
<td>11.52</td>
<td>2.46</td>
<td>3.31</td>
<td>18.55</td>
</tr>
</tbody>
</table>

Pointing Accuracy (arcsec)

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<tr>
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<th>Max</th>
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</thead>
<tbody>
<tr>
<td>6.97</td>
<td>2.16</td>
<td>-12.78</td>
<td>12.89</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>11.52</td>
<td>2.46</td>
<td>3.31</td>
<td>18.55</td>
</tr>
<tr>
<td>Roll</td>
<td>10.13</td>
<td>2.34</td>
<td>2.88</td>
<td>36.49</td>
</tr>
</tbody>
</table>

Table 4 Full State Estimation Performance (EKF+UVF)
increased from three to four, the localization error is greatly enhanced to 35.30 m as shown in Table 5.

<table>
<thead>
<tr>
<th>Geo-location Error (CE  0  35.30 m)</th>
<th>RMSE (m)</th>
<th>STD (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
</tr>
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<tbody>
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<td>X</td>
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<td>-129.02</td>
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</tr>
<tr>
<td>Y</td>
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<td>9.51</td>
<td>-37.40</td>
<td>31.08</td>
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<table>
<thead>
<tr>
<th>Pointing Accuracy (arcsec)</th>
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<tr>
<td>Yaw</td>
<td>2.84</td>
<td>2.78</td>
<td>-6.57</td>
<td>11.94</td>
</tr>
<tr>
<td>Pitch</td>
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<td>2.99</td>
<td>-12.23</td>
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<tr>
<td>Roll</td>
<td>5.87</td>
<td>3.55</td>
<td>-4.57</td>
<td>36.11</td>
</tr>
</tbody>
</table>

Table 5 Performance Enhancement using Four Stars (EKF+UVF)

5. CONCLUSIONS

A novel derivation of using the UVF measurement which can be applied to the ground processed precision attitude determination algorithms is proposed. The usefulness of using the UVF measurements over the QUEST measurements is demonstrated in a simulation result. The estimation performance when using the UVF measurements can be enhanced by increasing the number of the stars used for the estimation. However, the performance enhancement is expected to be saturated as the number of stars increase. Also it is expected that even the performance may be degraded because less brighter stars having worse noise characteristics are used for the estimation. Thus it is necessary to analyze the estimation performance with increasing number of stars used for the estimation together with the computational load, which is remained as a future research topic.

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REFERENCES