# On-the-Fly Merging of Attitude Solutions

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**Abstract** Recent advances in autonomous attitude determination instrumentation enable even small satellites flying fully autonomous multi head star trackers providing full accurate and robust attitude information. Each sensor provides the full attitude information but for robustness and optimal usage of the available information, i.e. optimal accuracy, methods for merging such data should be investigated. The need for and desirability of attitude merging depends on the mission objective and available resources. To enable real-time attitude control and reduce requirements on download budget, on-board merging of attitude data will often be advantageous. This should be weighted against the need for post observation reconstruction of attitudes, especially needed when end products are sensitive to optimal attitude reconstruction. Instrument integrated merging algorithms will reduce the complexity of on-board AOCS. Methods for attitude merging are many. Two examples of merging methods taking into consideration anisotropic noise distributions are presented and discussed.

## 1 Introduction

With the advances in development of sensor technology and onboard computational power, autonomous multi sensor attitude instruments are becoming the preferred choice even for small satellite missions. As an example, several small satellites (e.g. PROBA, SMART-1, PROBA-2, Flying Laptop and PRISMA) are now featuring autonomous multi-head star-trackers.

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Merging the individual measurements from several attitude sensors on a spacecraft has classically been performed in the on-board AOCS and when higher attitude knowledge is required on ground. However, with the computational surplus of state of the art multi-head attitude sensors, it is now possible to perform the attitude merging in the attitude instrument itself, while still enabling further improvements by post-processing on the ground. Despite that the process appears simple, this task is not trivial, since the relative orientation between attitude-sensors will often be non-constant over time due to thermally induces deformations in the spacecraft structure. Applied methods will, for optimal performance, have to take this into account, and reliably report the estimation of such biases and their variability.

There are several advantages of merging multi sensor attitudes in the instrument itself. Primarily, it reduces the complexity of the on-board AOCS sensor fusion module, which especially for small satellites can be desirable. Secondly, solutions incorporating measurements from several sensors will be more robust towards dropout of individual sensors. This is of interest to any mission, but especially to missions with relatively high agility requirements; e.g. in Earth imaging and formation flying applications. Also, combining the measurement data will improve the accuracy of the solution output from the attitude instrument. In addition to the obvious $\sqrt{(n)}$-noise reduction from two or more measurement of the same physical quantity, anisotropic accuracy distributions can be improved. E.g. for a star tracker, the accuracy of the determination of the roll about the line-of-sight can be reduced by a factor in the range of 5–10 (depending on sensor geometry) by combining solutions from two or more heads.

This paper presents the rationales for instrument-integrated merging of attitude solutions and discusses the pitfalls of this strategy. Two methods for merging attitude solutions are presented. These apply regardless of whether the merging takes place in the instrument, in the AOCS on-ground. An example of attitude merging results is presented.

## 2 Why Instrument Integrated On-the-Fly Attitude Merging?

Merging of attitude sensor data can be performed on ground (post observation) or on-the-fly (real-time), either in the on board AOCS core or in the individual multi-sensor instrument. A number of parameters should be taken into account when evaluating pros and cons for either approach.

On-the-fly attitude merging is characterized by real-time response enabling real-time agile attitude control. This includes both improved accuracy from merging two or more says on the attitude and increased robustness from immunity towards outages of individual sensors (e.g. blindings). These characteristics will be crucial to the overall mission success when the quality of the mission primary observation, obtained by e.g. telescopes, antennas or gravitometer, will be negatively impacted by lack of high accuracy attitude knowledge and control.

Secondary benefits include reduced downlink budget requirements and reduced costs of ground support operations.

**Table 1** Characteristics to be considered when evaluating on-the-fly vs. post observation merging of attitude data

| Characteristics | On-the-fly merging | | Post observation, on ground merging |
|---|---|---|---|
| | *Instrument merging* | *AOSC merging* | |
| *Response time* | Real-time | Real-time | Days to weeks |
| *Real time attitude control* | Yes | Yes | No |
| *Robustness* | High | High | Low |
| *Accuracy* | High | High | High |
| *Flexibility of merging method* | Medium | Medium | High |
| *Additional relative orientation model parameters available* | None-Few | Some | Many |
| *AOCS load* | Low | High | Low |
| *Bandwidth required* | Low | Low | High |
| *Science reconstruction possibilities* | Limited, requires download of all data | Limited, requires download of all data | High |

The main advantage of performing attitude merging within the individual instrument is the reduction of AOCS complexity and required AOCS processing capability as well as performing the merging at a stage where intimate knowledge of noise spectrum and distribution is well established. This is to be weighted against the benefits of performing the merging process in the AOCS, namely: Increased availability of additional parameters characterizing the S/C state, e.g. structure temperatures; full system level control over the merging process.

Post observation merging is on the other hand characterized by high flexibility and use-specific optimization of the merging method applied. This includes detailed modeling of internal S/C platform flexures. This is especially needed when very high accuracy attitude information over the full orbit (attitude and pose) and over many orbits (seasons and time) is essential to the mission end product but the primary observation is not impacted by less than optimal attitude control, e.g. geopotential mapping missions.

Depending on the mission attitude knowledge requirements and on-board processing resources, either strategy may be selected, but for some missions it may be necessary to have both the fast response of on-board merging and the possibility of post processing the full attitude information from all sensors. Table 1 summarizes the main characteristics.

## 3 Merging Methods

Merging of attitude information can be performed in numerous ways depending of the goal and available information. Here methods will be restricted to simultaneous measurements from two or more sensor heads providing the full attitude (all three degrees of freedom) in each measurement, as it is the case for multi head star trackers.

The attitude measurement gives the orientation of the sensor with respect to a reference frame (typically the inertial J2000 frame) and can be parameterized as e.g. a set of Euler angles, a quaternion or a direction cosines matrix.

Two important features characterize the merging method:

- Weighting. If weighting information in the form of noise estimates for the individual measurement is available this should be included in the merging. At least sensor specific information on anisotropic noise distribution should be used.
- Relative orientation of sensors. Either assumed to be constant or varying. If the relative orientation is assumed to be varying it may either be modeled against external information or simply filtered/traced.

When performing attitude merging it is essential to include knowledge about the relative sensor noise and the noise distribution properties. Relative sensor noise of normally specified as part of the measurement data in the form of e.g. a residual. Sensors will often have anisotropic noise distributions. For the star tracker example the direction of the boresight axis is determined with an accuracy, which is a factor 5–10 better than the accuracy of the rotation about the boresight axis. This is illustrated in Fig. 1.

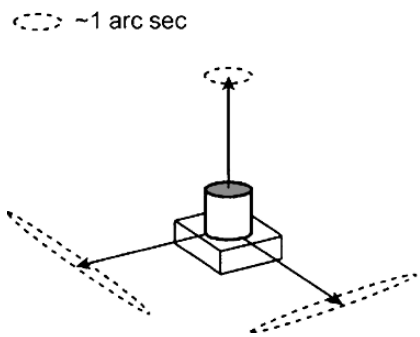


**Fig. 1** Example of anisotropic noise distribution for a star tracker. Dotted lines give the error ellipses for each of the three axis of the measurement frame. Since the pointing error typically is the same in all directions, the uncertainty of the pointing vector result in a small error circle. Since the roll noise is higher than the pointing noise, the error at lateral directions result in an error ellipse

When merging data with anisotropic noise distributions care must be taken to avoid worsening the overall noise. An example of this is shown in Fig. 2.

However including knowledge about the noise distribution can improve the accuracy of the merged solution relative to the two individual solutions. This is illustrated in Fig. 3.

For most S/C platforms the relative orientation between sensors will vary over time. This is a consequence of varying thermo-mechanical loads on the structure. Often a correlation with the orbit period is seen, an example of this is shown in Fig. 4. The magnitude of these variations will depend on the platform design, but

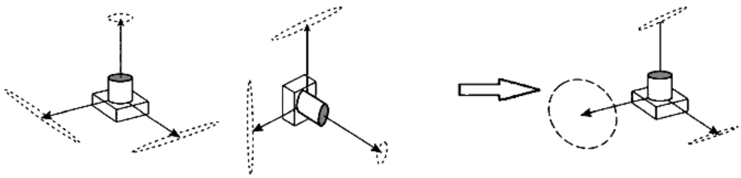

**Fig. 2** Example of attitude merging of two orthogonal star trackers with anisotropic noise distribution. Simple averaging of the two independent attitude solutions will lead to less than optimal attitude knowledge. E.g. if simple addition of vectors is used, the error ellipse is added to the small error circle for two axes giving a new ellipse, and the two error ellipses will add to a large error circle in the last axis

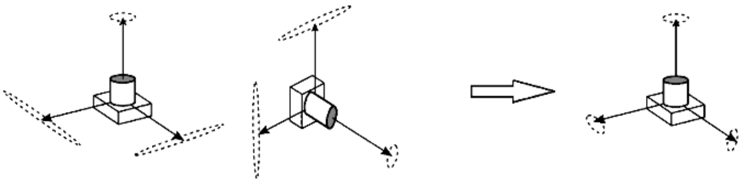

**Fig. 3** Example of merging method where anisotropic noise distribution has been taken into account

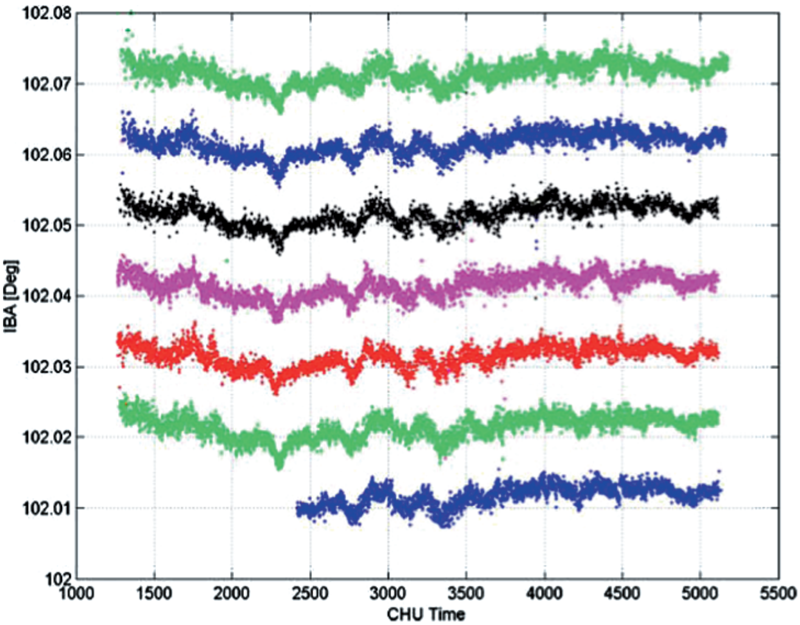


**Fig. 4** Variation of relative orientation between two sensors over 6 consecutive orbits. The relative orientation is represented by the Inter Boresight Angle (IBA). IBA is offset 0.01 deg pr. orbit for clarity

will often be in the range of several tens of arc seconds for standard platform structures. Very stable platforms can be achieved by careful design, i.e. the SWARM optical bench carrying vector magnetometer and star trackers aims at a sub-arc second stability through the use of ultra low thermal expansion coefficient materials combined with thermal stability control [1].

Stability of the S/C structure shall be taken into account both when designing the mission and when selecting the method for attitude merging.

In the following, two examples of attitude merging methods for star tracker measurements are given.

## *3.1 Merging of Two Boresight Directions*

A simple form of attitude merging of star tracker data is performed by merging the two line-of-sight directions into a single common reference frame [2]. This merging method utilizes the fact that for star trackers the boresight direction is more accurately determined than the rotation angle about this axis. The merging of the two boresight directions ($\nu_1$ and $\nu_2$) is performed by constructing:

$$\nu_a = \frac{\nu_1 + \nu_2}{|\nu_1 + \nu_2|}$$

$$\nu_b = \frac{\nu_1 - \nu_2}{|\nu_1 - \nu_2|}$$

$$\nu_c = \nu_a \times \nu_b$$

This orthogonal triad constitutes the merged common frame specifying the attitude and will carry the full accuracy in all three axes. Assuming a rigid support structure, the relative rotation ($R_{i-C}$) from each of the sensor frames ($i = 1, 2$) to the common ($C$) frame may be calculated for each attitude update. In case of dropout of one of the sensors, the common frame is constructed by offsetting the valid measurement with ($R_{i-C}$). In case of a non-rigid support structure filtering or parameterized modeling of ($R_{i-C}$) may be introduced.

This method does not support the introduction of variable weighting information but fixed weights may be incorporated if relevant.

Results obtained using this method is exemplified below. The example shows the merging for two sensor heads placed on a common bracket structure having an angle of 40 deg between the two boresights. The measurements were carried out on ground with two star trackers on a common mounting structure, operated at sea level, and thus show an elevated noise level relative to what is observed in space due to the influence of the atmosphere. Note the much smaller scale of the graphs showing the boresight direction (1st axis).

It is seen that the asymmetry in the noise distribution is significantly improved in the merged data, while maintaining the good overall performance.

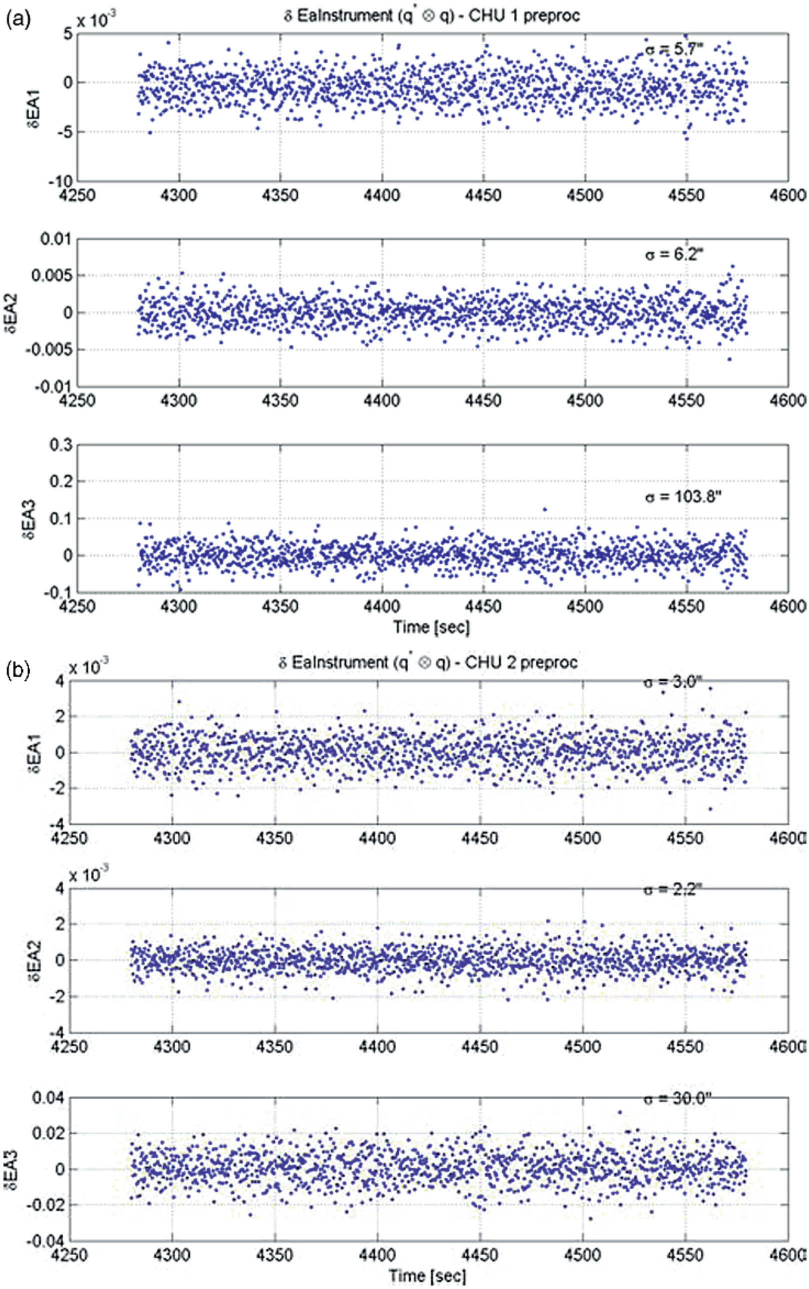


**Fig. 5** Noise estimation in native star tracker frame for two sensor heads obtained from on ground measurements. The anisotropic noise distribution is clearly seen

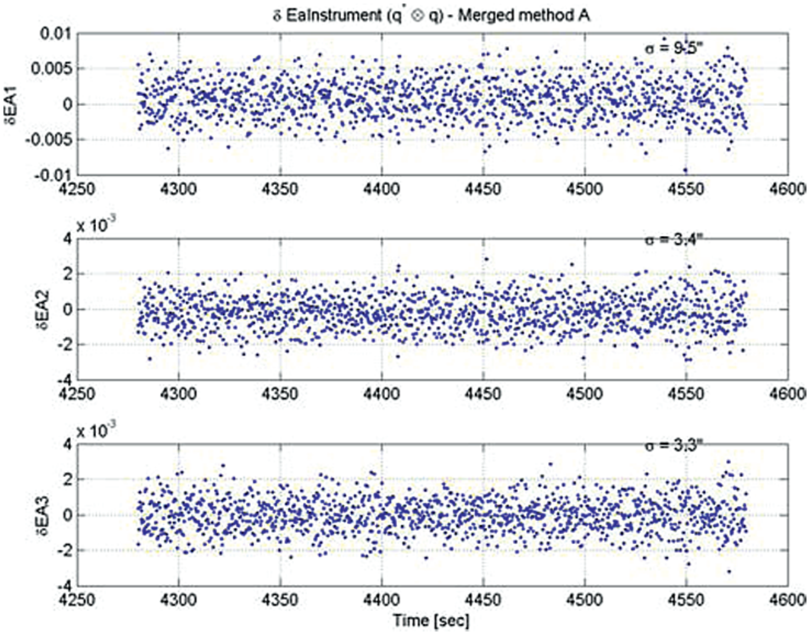


**Fig. 6** Noise estimation for combined attitude solution obtained merging the two boresights. Please note that the three axes are not the same as for the individual sensors

## *3.2 Merging of the Full Attitude Information*

Using the full attitude information from each sensor, any information on anisotropy in the measurement accuracy should be used in the merging process. A method achieving this is described in [3].

If the simultaneous attitudes measurements are represented by DC matrices ($R_{REF-i}$) and the orientation of the common frame ($C$) with respect to each sensor frame is $R_{i-C}$ is assumed fixed. The sensor specific noise distribution matrix $\sigma_i$ shall be transformed to the common frame resulting in $\sigma_{Ci}$.

$$\sigma_{C,i} = (R_{i-C})\,\sigma_i\,(R_{i-C})^T$$

The noise distribution in the common frame is then applied as weights for merging the individual attitudes in the common frame $R_{REF-C,i}$.

$$R_{REF-C,i} = R_{i-C}R_{REF,i}$$

Also for this method the relative orientation between sensor and common frame can be modeled or filtered depending on available information and application.

## 4 Conclusion

Merging of individual attitude solutions from multi sensor head attitude instruments is important for obtaining the optimal performance with respect to accuracy and robustness. This merging can take place within the instrument, in on-board AOCS or on ground. Advantages and drawbacks of either approach have been discussed. On-the-fly attitude merging is crucial to missions where the primary observation will be influenced negatively by less than optimal attitude knowledge. Other missions may do as fine with on-ground post processing. When selecting merging method it important to take into consideration weighting of the available attitude information, especially in the case of anisotropic noise distributions shall be included. Also platform stability shall be given consideration and if needed modeling or filtering of the relative attitude between sensors shall be included in the method.

## References

1. J.M.G Merayo et al. (2007) The Swarm Magnetometry Package, Small Satellites for Earth Observation, 6th International Symposium of the IAA, Berlin, April 23–26, 2007.
2. This method has been developed and used by GeoForschungsZentrum Potsdam on the CHAMP satellite.
3. L. Romans (JPL 2003), Optimal combination of quaternions from multiple star cameras.