BOEING

To: Astro2010 Decadal Survey Committee

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Subject: Star Catalog Concerns – Engineering Applications

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ABSTRACT

Spacecraft that require high-accuracy pointing use stars to establish and maintain an attitude reference. These systems require accurate data for the brightest stars in the sky. In the past, astronomers routinely observed the bright stars, easily outdistancing the requirements of the spacecraft navigation community. Today, however, a demand for increasingly accurate systems is paired with diminishing scientific interest in the bright stars used for engineering applications.

INTRODUCTION

Today's best star trackers observe objects with in-band magnitudes of 2.0 to 7.5 to a position accuracy of about 100 mas. Star intensity is often used as a star identification discriminator as well. To make the most of these instruments, the all-sky star catalogs used to support these systems should have true-of-date accuracies of 10 mas or less. Photometry serves an important role in predicting instrument magnitudes and evaluating the impacts of optically near neighbors.

Looking at today's docket, J-MAPS (Joint Milli-Arcsecond Pathfinder Survey) appears to be the only item on the manifest designed to observe bright stars. The fact that J-MAPS fills this void is no accident. The *Position, Navigation and Timing Joint Capabilities Document* approved by the Joint Requirements Oversight Council (JROC) on September 25, 2006, identified this bright star gap and became the primary driver for J-MAPS.

Assuming J-MAPS is fully funded and the mission is successful, the basic astrometric needs of the spacecraft navigation community should be satisfied for many years. But the broader space application issues are too diverse for J-MAPS alone. Even in the arena of visual astrometry, the fundamental issue of divergent requirements means that subsequent neglect of the brightest stars will eventually put us back in the same boat.

These concerns lead to a number of questions:

- Can the nation afford separate observing programs for engineering and science?
- Can detectors and systems be designed to observe the full intensity range of interest?
- Can the needs of both communities be served simultaneously?
- Can funding for joint missions be structured to benefit both communities?

If it is not feasible to address space application requirements using data generated by the scientific community, a new paradigm will be needed where spacecraft engineers and host agencies acknowledge an internal responsibility to perform the observations necessary to generate accurate bright star catalogs.

A joint science and engineering path has at least two potential benefits: (1) increased funding for science – as long as space application requirements do not derail scientific objectives – and (2) improved accuracy for engineering applications because astronomers have the needed expertise to make the most of celestial observations.

The CMOS hybrid detector design envisioned for J-MAPS suggests the objective of a joint path may be feasible in at least some cases. The bigger question is whether we can more generally broaden our observations to accommodate space engineering applications. My purpose is to encourage awareness and development of the technologies to make this possible.

SPACECRAFT APPLICATIONS

Star catalogs are used for a variety of space vehicle applications. High-level descriptions of the quality and character of these catalogs are provided in the following paragraphs.

Attitude Determination

Attitude determination is the most common engineering use for star catalogs. After a vehicle is launched, a “lost-in-space” algorithm compares observed star patterns with catalogue stars to initialize the onboard inertial reference. Once a vehicle’s orientation is established, differences between observed and catalogued star positions are used to continuously optimize the accuracy of this reference.

When creating star catalogs to support stellar inertial attitude determination, engineers search out or compile an all-sky input catalog that hopefully comes close to including all observable and potentially interfering sources. Application catalogs are a subset of this input catalog. Lost-in-space catalogs generally include all potentially observable stars. Catalogs designed to support ongoing attitude determination are more restrictive, including only those sources expected to support program requirements.

The pass-band for star trackers designed to support attitude determination generally covers the range of 500 to 900 nanometers. Many trackers reliably observe stars down to an instrument magnitude of 7.5. For the redder sources, instrument and standard visual star intensities can differ by as much as 4 magnitudes. For today’s most demanding applications, near neighbors up to 4 magnitudes or so dimmer than the observable source can cause unacceptable position errors. This means our input catalog needs to be as complete as possible out to a visual magnitude of 15 or 16 … today.

Payload Calibration

Star catalogs are also used for a variety of payload calibration activities. Engineers calibrate payload alignment by simultaneously observing stars in the trackers and the payload. Focal plane sensitivity is calibrated by staring at well-known stable sources and taking the differences between the expected and actual output. Scale factor calibrations are performed by sweeping stars across a sensor’s field-of-view. Some users point to darker parts of the sky to calibrate a sensor’s noise floor.

Payload calibration applications range from the visual to the infrared and generally do not require knowledge of all sources. Instead, most users only need a few dozen “clean” bright sources (or sometimes clusters of sources), preferably spread somewhat uniformly around the celestial sphere. If a payload contains multiple focal planes, engineers often hope to find stars that can satisfy requirements in all corresponding pass-bands. Unfortunately, many engineers are not aware that the use of visual astrometry for infrared sources may not provide the expected accuracy.

Other

Star backgrounds are used to isolate and characterize objects in the sky. Some applications subtract known sources from the sensor field-of-view to isolate and establish trajectories for these objects. Other applications use the background sky to observe relative motion and compute orbit parameters.

These applications also range from the visual to the infrared, requiring an all-sky catalog that includes all observable sources to the sensitivity of their sensors. Astrometric and radiometric knowledge must be good enough to support object identification.

REQUIREMENTS

In 2001, a working group comprised of industry engineers, government customers, consultants, and a handful of astronomers at the United States Naval Observatory gathered to discuss development of a long-term plan to meet the star catalog needs of the aerospace community. As part of this effort, approximately 20 star catalog users participated in a survey designed to gather requirements and expectations for the next 30 years. This section summarizes the results of this survey.

In the figures used to capture survey results, green pertains to the visual spectrum; red reflects inputs from users of the infrared sky. Bars show the range of requested accuracies for each decade and trend lines reflect the average requested accuracy. Just below each graph is a number line that captures the average level of importance attached to the requirement by the users; arrows reflect a perception of how this will change over time.

Astrometry

First, users were asked to specify a total allowable error due to a combination of measurement uncertainties (e.g. position, proper motion, and parallax), reference system errors, and interference from optically near neighbors.

The graph on the left half of Figure 1 shows what astrometric accuracy users believe they need for primary sources – stars they intend to observe and use to achieve their program objectives. On the right, they indicate how accurately they want to know the positions of interfering sources – objects they don't intend to use directly, yet might be impacted by if they are not aware of their presence.

Generally speaking, users felt they need to know the positions of primary stars more accurately than potentially interfering sources. Almost all users felt that 0.1 mas accuracy will suffice for the next 30 years.

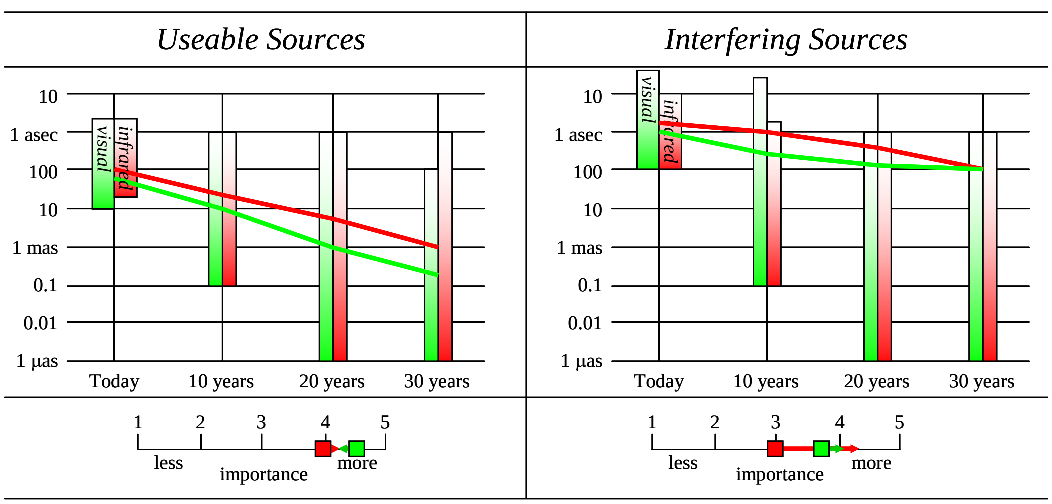

Figure 1. Survey Results – Astrometry

Photometry/Radiometry

Next, those surveyed were asked to specify a total allowable uncertainty in expected versus observed instrument magnitude resulting from inaccuracies in catalog photometry, catalog to instrument magnitude conversion errors, and unknown star variability. For primary stars, this information is critical to determine which stars can be dependably and accurately tracked. For potentially interfering sources, it enables a determination of the extent to which an object will affect the position and intensity of a nearby candidate primary star.

On the left graph of Figure 2, instrument magnitude accuracy requirements are shown for primary sources. On the right, users indicate how accurately they want to know the intensity of potentially interfering sources. Infrared sky users generally felt stronger about the primary source requirement – all the way from the near to very-long-wave infrared. In the visual sky, users were all over the map in their requests and the importance they attached to this topic. Most users felt that instrument magnitude prediction accuracies of 0.01 magn will be adequate for the next 30 years.

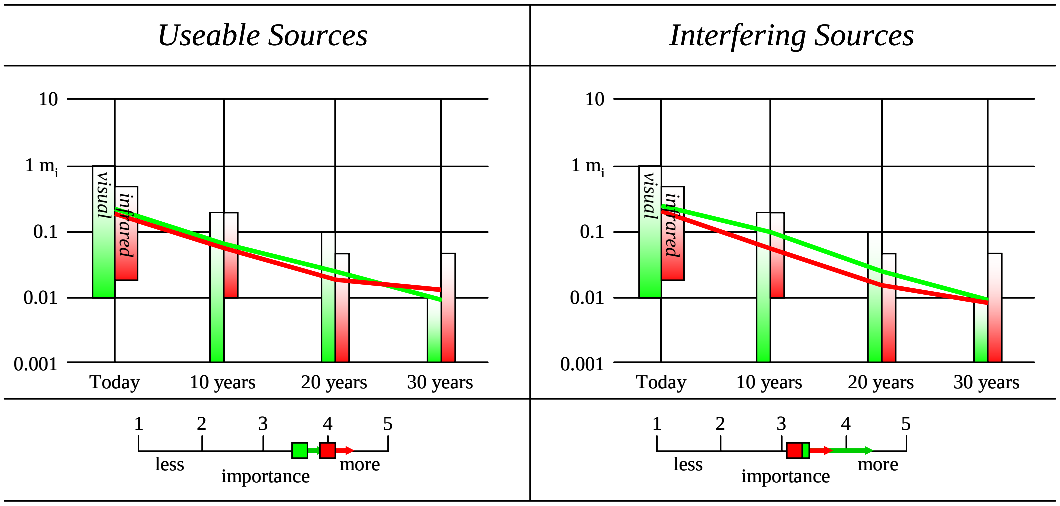

Figure 2. Survey Results – Photometry/Radiometry

Note: Instrument magnitude determination is problematic today, especially for redder stars and even in the visual spectrum. It is not unusual for users to be forced to change their flight catalogs after launch because a star turns out to be more than a magnitude dimmer or brighter than predicted for their sensor.

Completeness

The third category of questions related to catalog completeness and the range of magnitudes needed. Not knowing about a missing observable celestial source can be problematic for some engineering applications. Unknown objects can result in star misidentification and other undesirable effects. In the infrared, however, many engineers use a short list of calibration stars and only care about objects optically near a candidate being considered for their calibration catalog.

The shaded areas on the left graph below show a projection of how users expect the average instrument magnitude range to evolve for primary stars. The bars reflect the ranges for the brightest and dimmest acceptable stars. One participant listed our sun's apparent magnitude, which was ignored for purposes of this graph. There was a wide disparity regarding the importance of this requirement today, but all users indicated a feeling that this will be critical within 20 years.

The graphs shown in Figure 3 reflect an apparent inconsistency in survey responses. The average user only asked for knowledge of near neighbors within 2-3 instrument magnitudes of primary stars. Unfortunately, the effect of these optical or physical doubles on astrometry can be much greater than the accuracies requested for the astrometry portion of the survey. The user who indicated a need to know about near neighbors with delta magnitudes as great as 4 today and 10 within 30 years has a greater understanding of the impact. Achieving this level of near neighbor identification, however, could pose significant technical hurdles.

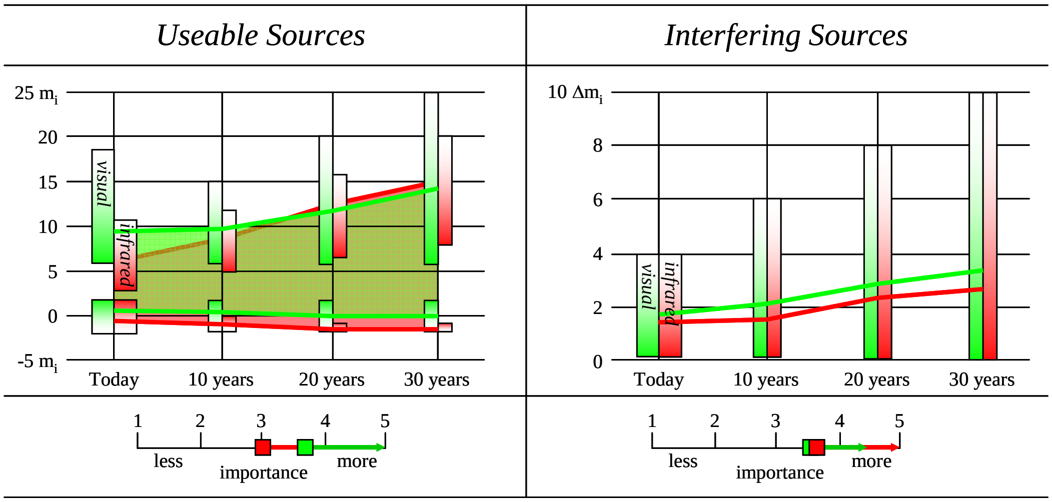

Figure 3. Survey Results – Completeness

Change Notification

Finally, participants were asked about the timeframe and importance of user notification of new data or changes in the sky. For instance, if a dim star becomes bright enough for a sensor to track, it may be misidentified by onboard attitude determination algorithms, potentially resulting in reference degradation or loss. Even if a star cannot be seen, changes in magnitude can affect the observed position of near neighbor primaries.

As reflected in Figure 4, most users were interested in notification of changes in how the sky will appear to their sensors. Many would like to know about such changes as soon as possible after they occur. Others felt this may be more important in the future. The infrared community showed particular interest in rapid notification of celestial events.

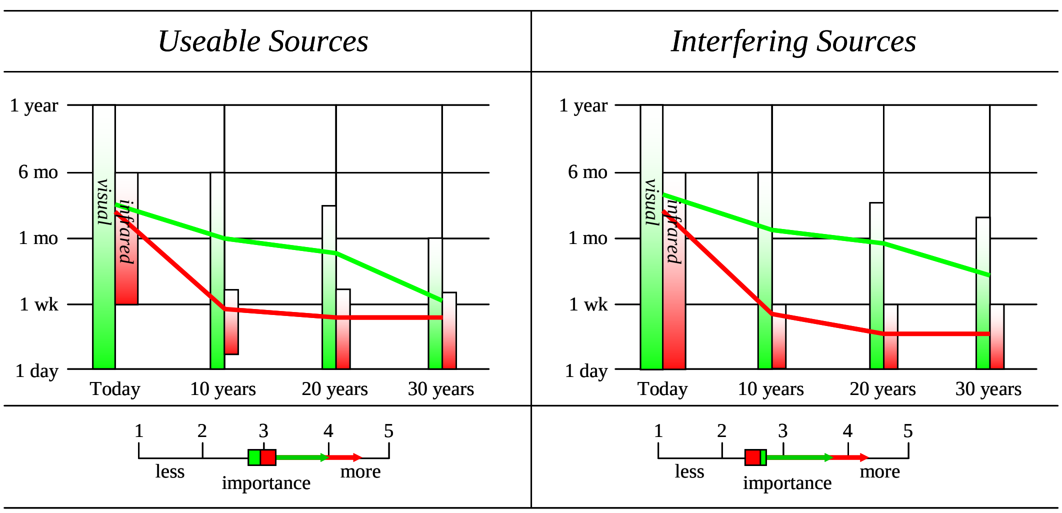

Figure 4. Survey Results – Change Notification

SUMMARY

Spacecraft that perform high-accuracy pointing missions require increasingly accurate information regarding the brightest stars in the sky. Science, on the other hand, appears to be moving away from bright star observations.

Government agencies with an interest in space have begun to notice this growing disconnect between scientific interest and spacecraft engineering requirements. The very existence of J-MAPS is evidence that some resources are being dedicated to bridge this gap.

But J-MAPS is just one program and cannot possibly address all of the issues. The better long-term solution may be to bring these communities back together through an awareness of space application user requirements, the development of detector technologies that support continued viewing of bright stars, and an understanding of the mutual benefits of combining our limited resources.

Your efforts to encourage technology development and observing programs that accommodate space application requirements are greatly appreciated. Thank you.