DISCUSSION CONCLUDING AAS 11-673

Neil deGrasse Tyson asked if it were possible to update space-borne ephemerides such that redefined UTC might become the explicit variable. David Simpson said that this could be accomplished by calculating a new series with UTC as the independent variable and uploading the new series onto the spacecraft. Tyson noted that the process of changing the independent variable seemed like it could be computer automated, thereby the cost of change in this situation seems pretty minor compared to other situations affected by UTC redefinition. Simpson clarified that without leap seconds series expansion itself should need to be re-generated. Frank Reed said that the recreation of a new series would be "child's play" and he could do it tomorrow. Simpson wondered if a lunar-model reformulation would be as simple as suggested.

Ken Seidelmann noted that there ought to be two other timing requirements for Hubble. One would be the antenna pointing for space-to-ground communications, which would seem to require UT1, and another for tracking solar system objects, which would seem to require a dynamical or coordinate time scale. Simpson clarified that the issue of ground communications is mentioned in the written paper but was omitted from the presentation. In addition to the lunar and solar ephemerides, a spacecraft ephemeris is also maintained onboard. Additionally, there is a simplified two-body ephemeris maintained onboard for the TDRS geostationary communications satellites which uses UT1 as its independent variable. This is used to compute the direction from the spacecraft to the TDRS satellites for proper antenna pointing. Seidelmann said the accuracy requirements on those ephemerides should be more critical than the lunar and solar ephemerides. Rots said that he performed a calculation at 500 km altitude assuming a one-second error, and that should introduce a maximum error of about 3 arc-minutes with a geostationary object.

With regard to tracking solar system objects, Simpson said that an explicit ephemeris is not used. Instead, a bias is introduced into the spacecraft attitude-control law which allows the telescope to slowly drift in order to follow a moving object. Seidelmann wondered if timekeeping issues affected the anticipated fields of view which are quite restricted for some instruments. Simpson replied that could be handled on the ground as part of the bias calculation, but agreed that this would still need to be handled properly within the ground calculations. Rots and McCarthy asked if star trackers were used for orientation. For Hubble, Simpson said that wide-field star trackers are used in conjunction with the Fine Guidance Sensors. McCarthy responded, "When you do that, this always falls away and you are just using your internal calibration and your platform."

McCarthy said that he did not understand how a lunar ephemeris could be produced relative to UT1. Kaplan said that was a good question, that he was aware of the formulae being cited, and that he would investigate as soon as possible, because the creation of lunar and solar ephemerides in terms of UT1 seemed unnatural. Kaplan said that if UT1 was the independent variable, then someone had already applied a model for ΔT, because normally such ephemerides are a function of a more uniform time scale like TT. Simpson noted that the independent variable used throughout the *Astronomical Almanac* labeled "UT" he would interpret to mean "UT1". Kaplan noted that UT is used primarily in the *Almanac* wherever Earth orientation is of primary interest, but not

for solar-system ephemerides. Seidelmann wondered if these expressions originated from the navigation departments, which tend to reference UT. Kaplan said that ΔT model would still have been necessary for UT to have been used as the independent variable. McCarthy said that he would be interested in knowing what was used for ΔT. Kaplan said the model for ΔT could be years out of date, and certainly the people who formulated these equations probably never anticipated that a mission like the Hubble Space Telescope would be using them. Simpson said that the model was not used blindly; the series were compared against the DE200 lunar ephemerides and the errors were observed to be well within allowable tolerances. Tyson commented that this level of testing seems to affirm that a ΔT model was in fact used. Simpson reiterated that the independent variable in the analytical lunar model is time T in Julian centuries elapsed from epoch J2000 on the UT1 time scale. Reed noted that since the accuracy of the lunar ephemeris was measured in terms of fraction of a degree, the precise definition of the independent variable was not consequential to that case, to which Simpson agreed.

Seaman asked a rhetorical question about the degree to which "flight software" has been investigated regarding a possible change in the definition of UTC. Simpson agreed that this issue "tends to be low on people's radar" and speculated that many people have not heard of this issue, and therefore concluded that there has likely been little to no study. In order to look into the ramifications, someone at the management level would first have to decide to spend money to execute an impact study, and Simpson said that he was not aware of anyone within NASA who had done this.

McCarthy said that he imagined that the flight instrumentation is calibrated to an onboard clock and that onboard clock could be calibrated to whatever time scale is preferred. Seaman responded that in relation to a process, a phrase like "I imagine" would indicate that planning should have happened that did not. In response to McCarthy, Terrett offered that there is the potential for confusion as to what that time scale ought to be if UTC is redefined. It might be still be labeled or thought of as UTC, but if onboard clock oscillations were tied to something other than redefined UTC, then that could result in data-processing complications. Seidelmann said that it is an issue between the time-tagging of the instrument data, the spacecraft, and the telemetry data, and the meaning of those times relative to other events. Simpson suggested that the few people at NASA who might actually know about this issue may be waiting to see the result of the ITU-R vote before spending any money toward this.

Rots said that he did not see a significant issue here, and that time tagging relative to TT seems to make more sense anyway. He said that his spacecraft telemetry data are received tagged relative to UTC; the first task is to convert these tags to TT with systems that must be aware of leap seconds. The only confusing aspect from this conversion is there is a minority of users that do not pay sufficient attention and presume that these data are still tagged to UTC, but that is a different issue.

Seaman asked how UTC gets into the telemetry stream. Simpson said that in his experience, the telemetry is actually tagged according to the onboard clock counter and it is the task of the ground crews to correlate that count to whatever time scale is required. Tyson said that the analysis of astrophysical phenomena in the time domain is a burgeoning frontier, so the precise synchronization of clock times between different instruments tied to different epochs will only grow in importance. Simpson said that for time-critical applications (*e.g.*, gamma-ray bursts) one would probably embed some kind of precision time within the science telemetry stream itself. On further reflection of his earlier statement, Tyson offered that data transformations are routinely performed all the time, citing the calculation of stellar coordinates as an example. Rots said that a

star tracker which is calibrated against guide-star coordinates from the ICRF catalog will inherently provide results relative to the ICRF; in that case no transformation is involved.

Reed asked how the simple orbital elements of the TDRS satellites were handled, as he was curious how often the elements needed to be updated due to the simplicity of the dynamical model. Simpson said that all of the ephemeris calculations were handled by the same code in the original DF-224 onboard computer, but when the HST was upgraded to an i486 onboard computer, an optionally simplified model was provided that took advantage of the fact that the TDRS spacecraft is always kept over the same spot on Earth. Called "TDRS-on-a-stick", the model assumes that the TDRS spacecraft are physically attached to the equator of the Earth and rotate with it at a given longitude. Seidelmann noted that in this case, onboard knowledge of UT1 is seemingly required because the TDRS model is explicitly tied to Earth rotation. Rots reiterated that a one-second orientation error should cause about 3 arc-minutes of pointing error.