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Time and Polar Motion in Early NASA Spacecraft Navigation

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Abstract. Inclusion of Polar Motion and UT1 data (corrections) is essential to achieving the full accuracy in NASA (and other) spacecraft navigation. Tracking station locations are routinely determined to the meter-level and must be available inertially (on the rotating Earth) to equal accuracy *a priori* in real-time. This implies knowledge of UT1 to 2.5ms and polar motion to 1m (and for practical use for the first time accurately predicted and disseminated to the navigation computer programs). This was essential from 1965 onward as we prepared for Apollo, for Apollo itself, and all subsequent missions. This paper presents the history behind the author's "discovery" circa 1965 at JPL that UT1 and polar motion were not then included in NASA's Orbit Determination models and programs; how this omission was being "observed" in station location determinations (and errors) from spacecraft radio tracking data; how it was rectified; the essential nature of these data in precision spacecraft navigation including Apollo; and how this became undoubtedly the highest and most critical application of these data in history. There followed widespread recognition of the many observers present and past who tirelessly and often with little visibility outside of professional astronomy made the necessary observations and calculations. As an historical paper, there is room for a few interesting anecdotes and personalities in NASA, as well as the late and much missed Dr. Markowitz then head of the USNO time service, and his successor Dr. Klock, with both of whom the author had the honor, professional benefit, and great personal pleasure of working during this time.

1. Introduction

I am taking an informal approach to this paper, as also at the reading. Historical papers of this kind are suited to abandoning most pleasurably on these rare occasions, our usual rather dry and impersonal scientific styles.

We go back to circa 1966, at the Jet Propulsion Laboratory of the California Institute of Technology. I was a "new boy" of less than one year's tenure, in what can be reasonably described as the spacecraft navigation group under Donald W. Trask. The "old boys" weren't that old, actually, 2-4 years in most cases. I was a retreaded high school mathematics teacher and amateur astronomer, my colleagues ranged from civil engineers to imported European university profes-

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sors. We were in many ways, the original "oddball team," which was, I think, in the end, a key advantage.

We were the responsible organization for spacecraft navigation of all unmanned USA spacecraft (JPL's primary mission), and with support for forthcoming Apollo navigation including tests and verifications from the Lunar Orbiter (unmanned) spacecraft. The latter concerns us in this history, particularly the tests of navigation accuracy at the Moon as determined from the reduction of real-time and stored data from the lunar orbiter spacecraft.

2. Basic Spacecraft Navigation

A spacecraft in orbit about the Moon is tracked (as are all spacecraft) with a radio-based, coherent, two-way doppler system. In a nutshell, the ground tracking stations (*e.g.* Goldstone, California, Spain, Australia *et al.*) maintain the best available and practical atomic clocks synchronized to the relevant national standard (in our case the National Bureau of Standards near Denver, Colorado). The uplink radio carrier frequency is locked to a fixed multiple of the reference atomic clock signal. It carries the commands and data uplinked by modulation in the usual ways. At the spacecraft, the received frequency is coherently (locked) multiplied by a given integer fraction (ratio of two integers), and retransmitted to Earth together with the downlink data. The uplink and downlink signals (at distinct frequencies) are simultaneously transmitted and received at the same antenna (I always thought that was the cleverest idea and the most challenging of design requirements).

The downlink carrier is then multiplied by the inverse integer fraction, and differenced with the uplink carrier. This "doppler" difference is the navigation datatype of preference. We did do ranging also, but at this epoch, it was generally not competitive with doppler. The accuracy is extremely good. For a one-minute integration time, a velocity can be measured with an accuracy of a fraction of one millimeter per second (in the presence of spacecraft velocities of kilometers per second). Over a period of time, suitably processed with a "model" of the solar system in the Orbit Determination Program (ODP), extremely high accuracy in navigation could "in principle" be achieved at the Moon and elsewhere in the solar system. The devil is, as always, in the detail. This is the story of one such detail which affected many people and astronomical services around the world.

3. Navigation Requirements

For Apollo navigation it was necessary early-on in the program (circa 1963) to specify the accuracy requirements. Studies were performed, and it was believed that an accuracy of 200m 1-sigma could be achieved, and this was thereafter quoted. It was the job of a number of navigational personnel to achieve this, and we weren't doing all that well in 1966, and even in 1968 (but that's another story). First things first.

To navigate using the doppler tracking system it was necessary to determine the locations of Earth tracking stations along with a host of other Earth-based and solar system parameters. We are concerned with the first of these. Since the Moon is roughly 60 Earth radii distant, a station location error of 3m would translate into 180m at the Moon. It had been calculated, and demonstrated with actual spacecraft data, that station location errors could be reduced to less than this amount. It is also true that there is some cancellation of errors, or amelioration, in any "fit" to data, and the whole of station location errors would not necessarily appear directly in errors demonstrated at time of landing upon the Moon. Nevertheless, 3m was our target, and it was being achieved, except for one problem which came up around this time.

4. Time and Station Locations

One cannot use station locations in the intertial framework of interplanetary space without knowledge also of the rotational position of the Earth in that frame. This latter is an independent observable which at that epoch had to be obtained from outside sources. This outside source was the NBS at Boulder, Colorado, via time signals received at the tracking stations, and added to the doppler and other data in the tracking files, sent on to JPL and elsewhere in NASA for processing.

I became involved in this aspect of our mission by accident, as I was not initially assigned to the lunar orbiter data analysis subteam. It happened that I needed the answer to a (probably) quite basic question, and did the usual JPL thing of walking down the hall and consulting an expert. There is nothing so efficient, not to say delightful, way to learn, and I was learning a lot every day (so were we all but particularly the new lads). The question, long forgotten, was answered in the office of William Sjogren, in the presence also of other members of that team, including C. Vegas and W. Wollenhaupt if memory serves.

It was the end of the day, and the team went back to their informal discussion of a problem which had arisen. It seems that "last September" and again "this February" (if memory serves), the station locations being determined in the re-fits to these parameters had jumped 40m. Dates? The "glitches" seemed to occur right around the first of these months, and maybe, now that memory was being recalled, once or twice before in the last two years or so.

My ears twitched, to be sure, since as an amateur I had dealt with the conversion of UTC to UT1, listening also to the time signals and so on, an everyday thing in those circles. Surely this couldn't be the problem. But the numbers spoke clearly; first of the month, 40m (0.1s at 400m/s). One could have been coincidence, two was unlikely. So, rather haltingly, I spoke up. "Could there be an error in the time? Time signals? Where do they come from? How do you get them into the program (ODP)?"

The answer was as above, the time received by the station from NBS = being imposed directly in the data-stream. "What about the occasional = offsets, corrections to UT1?"

I do not wish to slant this as the new guy putting the old hands right. It wasn't like that at JPL, nor in most other successful institutes and laboratories. These gentlemen listened patiently and thoughtfully, and I was only passing on a part of the astronomical culture which had by chance not been among the thousands of other parameters which various members of the teams had dealt with in order to create the Orbit Determination Program and the considerable expertise needed to apply it to real data. It was simply my turn to put a finger on one of the several missing links we still needed to tidy up along the way to a successful navigation of Apollo to the Moon and for the other missions. Presumably that's why we were hired, nothing more, nor less. And a feather in the cap, yet again, let's hear it for the amateur astronomers around the world.

5. Putting it Right

I believe it was Chuck Vegas who said something like, "Okay, sunshine, go up to the blackboard there, and calculate which way the stations should jump if we have missed this adjustment you speak of." I tried my best, but one is always wary of this the most error-prone of basic physics calculations! I finally worked out the direction, and quoted it. Happened to be right, probably by good luck!

It was now quite late, and as a recently married man, it was prudent to head home. Next morning, early as was my custom, was a note from the boss, Don Trask. "Come to my office immediately." This had impact, to say the least, as this gentleman is one of the strongest and calmest of men even in crisis I had ever met.

"Okay, Paul, how certain are you of all this nonsense about our having the wrong times in our programs?" He offered a mock seriousness of which I could not be quite certain one way or the other. Rather to be hung for a lion than a lamb, I replied, "Uh, well, quite certain sir."

"Then you had better get set up, and fix it, don't you think?" The smile said all. I was also rewarded with cooperation from all concerned around the world thereafter, who courteously and in a friendly colleagueship supported me, first in my ignorance (for example I knew nothing of polar motion) and later as I did my more fully informed work as timekeeper to NASA during the Apollo interval.

One fondly remembers the memory of William Markowitz at USNO. I remember clearly our first phone call. Perhaps somewhat fuller of myself that I ought to have been, he was gentle with me, but it was necessary to think about UT2, UT0, and had I considered corrections for polar motion? "Polar, what?" was my shocked response, and the beginning of both personal meetings and by telecoms.

6. Operations

Finding out what is wrong is one small step, fixing it is a journey. A pleasurable one as noted. Spacecraft tracking in real-time required time and polar motion in real-time, indeed it required predictions for reasonable intervals to be a practical addition to the programs. These were both new requirements.

I dealt with the second and created some computer programs to extend UT1 predictions (not particularly difficult because for mission-critical applications we would use up-to-date data with a very short prediction interval). Polar motion was more interesting, in that predictions were not a matter under discussion in the open literature. We, with the advice of several researchers in the field, used a method of prediction based on the previous great cycle of several years during which the amplitude cycles from very small to maximum. This is easier to do than explain. The literature we generated was in internal memoranda, and I do not recall any external publications. I would appreciate hearing from any colleague who has evidence of anything we presented in the open literature as my records from that era are not equal to such a search.

The key issue was to obtain fit, reduced, quotable up-to-date time and polar motion. The institutions such as the BIH and the ILS were not geared to this. Astronomers are happy with month-old and year-old quality fits. They want the final word so as not to have to re-reduce or re-correct data and results later. We had exactly the opposite problem. We needed the best, right now, today, so that the Apollo astronauts could land within their safety zones (on the landing maps and simulations) of 200m.

It is an understatement to say that the world astronomical community rose to the challenge. Dr. B. Guinot at BIH in Paris coordinated contacts with the many observatories and other services involved. I instituted a contract for their services, and NASA funded it in due course. It was a particular pleasure to meet Dr. Guinot at the conference, as we had met only once before, shortly after Apollo in 1970 I believe, by then a courtesy call to thank him for all his hard work. We also worked with B Klock at USNO when Markowitz retired, as did Henry Fliegel who took over as NASA timekeeper when I went on to other work circa 1972.

We created data sets which NASA used throughout all spacecraft missions, and continue to do so to this day. All of this contributed substantially and significantly to the successful precision landings on the Moon by the Apollo astronauts and added materially to their safety and the grand success of those and other missions to the planets. It is certain that this was a perhaps surprising, sudden interest in these data which had tirelessly been observed, reduced, and disseminated to astronomers for nearly a century at that time, a centenary which the IAU conference celebrated most appropriately in Cagliari. Indeed, the date 1967 was quoted by two presenters on the first day as a turning point in the various programs. The requirements noted here were perhaps pivotal at that cusp in this corner of the history of astronomy.

Ed. Note. Dr. Klock, to whom the author refers, did not succeed Dr. Markowitz as Director of the USNO Time Service. Dr. Klock served in the Transit Circle Division of USNO.