Shuttle/Tether Relative Motion During 'Swarm' Observation // Jim O // July 2014

The focus of this essay is on the geometry of the Columbia-TSS encounter, and the ranges and viewing angles. It's led me along very interesting paths that I'll be sharing.

The major surprise to me was the degree that the tether/TSS was "off to the side" of the shuttle and not 'above' it. Even on observation-2, with the famous 'swarm', it never got above 30 deg elevation to the inertial horizon [the Earth horizon was about 20 deg below that].

This was because the TSS/tether orbital plane had actually shifted away from the shuttle's plane by a significant amount, a value I had never bothered to calculate before and another delightful surprise for which I have to thank the guy who asked the insightful question for. My own original assumptions were too superficial. That's always a pleasure to discover and correct.

So the third and fourth observations were very low on the horizon, as described on the videos. The second, and best, was off to the side and 'back' away from sunrise. The first, as I had guessed, was in 'front', the same side of the sky as the rising sun, which explains the low quality of the video.

DETAILS

The relative motion between shuttle 'Columbia' and the separated TSS-1R payload and tether during the crew's observations on Flight Day 9 [March 1, 1996] turn out to be a lot more complex than earlier simplistic reconstructions imagined. The actual profile, now confirmed with computer simulations from two independent sources, directly bear on what was being seen, photographed, and shown on televised scenes by the on-duty astronaut team of Jeff Hoffman, Claude Nicollier, and Franklin Chang-Diaz.

After the tether snapped four days earlier, the satellite had been thrown into a higher, slower orbit. Columbia pulled ahead and then, over the next several days, overtook the tether from behind and below, and finally lapped it about a hundred hours after initial separation.

But the fly-under path was far from the simple directly underneath pass that observers imagined. Several factors of orbital mechanics influenced this.

Most important was the shift in the orbital plane of both satellites, but each at a different rate. This difference was due to the tether's higher altitude, where its path was affected slightly less by the gravitational torques of Earth's equatorial bulge. As a result, although 'Columbia's orbit was twisted westward at a daily rate of 7.49 degrees, the tether's rate was only 7.24, leaving an inertial orientation difference after one full lapping [four days] of 1.14 degrees. Combined with the orbital inclination [28 deg] this created a planar difference of 0.52 degrees. That difference in latitude is 52 NM, or ~100 km.

In practical terms this meant that far from passing overhead, as viewed from Columbia the tether was swinging left and right every orbit. Visualize a driver in the center lane of a three lane highway with a wild driver ahead, who is swinging from far left to far right lane and back again. Because the tether was in a higher orbit [between 20 and 110 km higher] there was no risk of collision but the left-right-left swings would still be dramatic. In orbital terms, the swing distance to either side was about 60 kilometers.

The secondary complicating factor is that the TSS-1R target was in a highly eccentric orbit. It had started out tethered 20 km above 'Columbia', at the same orbital speed. But the break threw it into a higher orbit, reaching out as far as 110 km higher. Soaring higher, its speed dropped, and then it swooped lower, regaining its initial speed – again and again and again.

As a result, back on the three-lane highway analogy, it's as if the swerving car stepped on the brake in the right lane, increasing your own overtaking rate, and then accelerated as it swerved to the left until it was almost holding its own, not appearing to fall back at all. The left-right swings continue, but the overtaking rate was quite different, right lane versus left lane.

As a result of the actual geometry, the tether does NOT pass directly above the shuttle, but off to one side or the other. Depending on where it is on the left-right-left swerving, it generally lurks near the straight out horizontal viewing vector [a few close passes are as high as 30 degrees] At Columbia's altitude, 'straight horizontal' is still well above the actual earth horizon, which for 290 km is 17 degrees down. So the tether is somewhat above the horizon during the observation periods, but nowhere near overhead.

Now add in the critical factor of illumination, which determines where along each swing the target satellite can actually be seen. First, for 40% of each orbit the tether is in Earth's shadow and is dark. Then, at sunrise, the tether can be seen. At sunrise, on this particular mission, the sun is about 30 degrees right of the direction of motion [this is called the orbit's "beta angle"], so viewing in that direction is difficult. And as the target swerves left and right, and as the sun 'rises' higher in the sky, glare effects on shuttle windows make the dim satellite unobservable.

Columbia's dark periods on the part of the day in question were 03:25:18 to 04:00:02 GMT, 4:55:36 to 05:30:22 GMT, 6:25:54 to 7:00:41 GMT, and 07:56:12 to 08:31:00 GMT Several minutes after sunrise would be the best viewing opportunity.

Shuttle flight plan documents and MCC time callouts are more often in Mission Elapsed Time, or MET. To convert MET to GMT for STS-75, add 51/20:18:00, the GMT date/time of mission launch. A third time hack needed here is the tape clock time on the three hour-long hi-def tapes on youtube, to reference exact mission comments. The NASA document "STS-75 Scene List" spells out both GMT and MET, but the tape time had to be measured during actual playing of the videos.

Now for the precise angles and times for STS-75. They were calculated by two expert sources and compared to the transcript I prepared from the hours of videotapes that spanned the four observation periods of the Flight Day 09 fly-under. They used public orbital data and can be replicated and verified by anyone with public domain s/w such as the "Satellite Tool Kit". Here are the results.

Columbia had been commanded into a special observation attitude described in the FD08 update message as –ZLV, -XVV, which means -Z axis [body up-down] as local vertical, -X [body long axis] in the velocity vector. This put Columbia moving tail forward, payload bay pointing to space.

First observation: Sunrise was at 04:00 GMT, the tether was at near far right elongation [and greatest altitude]. Azimuth was 068 deg , range was 527 km, elevation 009 deg above horizontal [and this 026 deg above visible earth limb].Over the next ten minutes the azimuth shifted to 075, elevation rose to 014 [i.e., 031 to earth horizon], as range dropped to 402 km.

This is the period when the crew got their first look at the tether, although the video images were poor. Viewing angles out the forward left window [in the commander's seat] were already near the trailing edge, looking hard to the left from the seat. But the aft cabin windows were worse, they directly in the glare of the rising sun at azimuth 033. Over the next ten minutes the sun moved halfway up the sky [40 degrees] so the crew then also tried the aft window, without much improvement.

Columbia was out of contact during this post-sunrise period, so the exact times of the observation were not recorded. The sequence was taped and then downlinked a few minutes later [04:31 to 04:39] with crew comments.

During the following period the full daylight glare rendered the tether non-observable, it continued its swing right to left, passing above and in front of Columbia. Reaching maximum leftward swing while also its lowest altitude, it briefly kept pace with the shuttle before beginning the swing back to the right. Sunset occurred, and about ten minutes later the tether passed right in front of and above the shuttle's nose, about 85 km out, unseen in the darkness. It then continued its swing to the right and reached maximum off-angle.

Second ["swarm"] observation. Sunrise occurred at 05:30 [the tether 'rose' about a minute before Columbia due to its higher altitude], at a range of 146 km, off to the right but now slightly trailing. Near its max altitude, the tether was high in the sky as viewed by Columbia. Cameras C and D in the payload bay were in use, and it would have been clearly visible in the overhead window.

Note that for this pass the line of sight to the upper right was in the vicinity of the shuttle's water dump ports along the left side of the crew cabin [which was pointed backwards for this observation period].

During this period Columbia was passing points 002N 007W to 019N 027E.This was predawn [but sunlit in space] from the coast of Liberia to northern Sudan, continuing across Saudi Arabia, Bahrein, towards Pakistan. It would have been bright in the predawn skies of West Africa all the way across Nigeria. The tether would have been much dimmer by comparison, but any other really large objects would have been starkly brighter a good distance away.

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The other question about comparable viewing angles in shuttle-body-axes is very important. To know that precisely, one needs to know the orientation of the spaceship relative to local vertical local horizontal -- LVLH, we abbreviate it. Then you need the camera's pan and tilt angles, which are digitally included on each frame but need special processing to display -- although sometimes if you have recognizable spacecraft structure in the FOV you can make a rough guess.

Coming into the FIRST observation period, say at sunrise at 7/07:40, on page 2-16 of the flight plan, note the row near the bottom called 'attitude'. For the interval in question it reads 'BIAS -XLV -ZVV', which describes a small offset from the -X axis [out the tail] standing locally vertical [LV] pointed to center of Earth, and the -Z axis [straight up out of the payload bay] pointing straight ahead [Velocity Vector]. That's more or less the spaceplane flying nose up, topside forward, wings out to left and right broadside to the direction of motion.

The precise attitude that is typed into the autopilot was spelled out in detail on flight plan page 3-64, at about MET 7/02:15, as follows: MNVR BIAS -XLV, -ZVV, specifying 'target' as earth center and Body Vector as -X, out the tail. The spacecraft then applies three rotations, a pitch, a yaw, and a roll of the three angles, which are close to, but slightly biased off of, orthogonal.

But look in the update packet for FD08, message 090A, FLIGHT PLAN UPDATE. To give the crew the best viewing angles the attitude is CHANGED to -ZLV, -XVV. That's flying bottom down to Earth, tail forward.

You can look at a model and realize that the first view would be through the aft cabin windows [which are facing more or less straight ahead] and as you approach the higher satellite, you begin to get a view out the overhead and then forward windows. That explains Hoffman's comments of which windows they were filming through, and when.

But the next observation passes would not occur until after Columbia had pulled ahead of the TSS-1R, so at sunrise it would be visible out the forward windows [the trailing windows] and awkward to film. So instead, payload bay camera C [on the aft bulkhead], pointed over the nose [and hence directly backwards as the spacecraft moves along its orbit tail-first] on the same side of the spaceship as the water dump port.

Yeah, this really IS 'rocket science', but it's critical to understanding the illumination and observation angles on these videos. Making wild guesses without taking these context factors into account is a waste of time.