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HUMAN LANDING SYSTEM (HLS) PROGRAM WHITE PAPER: HLS NAVIGATION BEACON

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Application of Navigation Beacons with the Human Landing System

Introduction

Navigation beacons have the potential to provide independent navigation measurements that support difficult precision landing and in-space state knowledge challenges. NASA analysis has shown that beacons not only support these requirements, but do so by also supplementing gaps of other navigation technologies. The purpose of this white paper is to document prior findings on how beacons can support navigation needs of the sustained phase of the Human Landing System (HLS) program.

Beacons and Lunar Landing Accuracy

NASA analysis has demonstrated how lunar beacons can reduce reliance on passive optical Terrain Relative Navigation (TRN) for achieving required landing accuracy. This is important as it was found that in a Design Reference Mission (DRM)[1] that descent trajectories traverse significant amounts of shadowed surface terrain (Figure 1). This degrades or eliminates the expected navigation performance of passive optical TRN. For vehicles or systems dependent on passive TRN, this created challenges in mission design and descent optimization when descent parameters such as approach vector, minimizing delta V, lighting, and maximizing the number of mission opportunities during a given time span were accounted for.

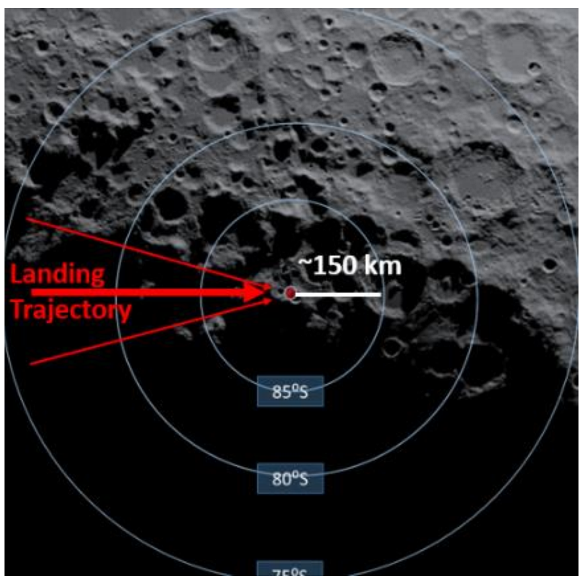

Figure 1: HLS Lighting on Approach to the DRM Landing Site

Because passive optical TRN systems, similar to what was used on the Mars 2020 landing, will likely be unable to produce accurate measurements when only shadowed regions are in view, alternative sensors may be desired. While several options, including active TRN, might be pursued to reduce reliance on passive optical TRN, this section will discuss the potential use of lunar beacons as a sensor solution.

Beacon Performance Analysis for Precision Landing

A navigation study was conducted to compare descent vehicle sensor suites and their ability to provide the vehicle with adequate state knowledge to realize an accurate landing. For this analysis, an accurate

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[1] Design Reference Mission was developed by NASA prior to Appendix H to work mission challenges without utilizing proprietary data

landing is defined as one where the vehicle lands within 100m of its intended target. Trajectory and navigation knowledge dispersions were generated using a linear covariance technique which can estimate the combined effects of Guidance, Navigation, and Controls (GNC) on those dispersions. The sensor suites assessed during this analysis contain combinations of the following sensors:

- Deep Space Network (DSN) State Update
- Navigation Grade Inertial Measurement Unit (IMU)
- NASA Navigation Doppler LiDAR (NDL)
- Medium Quality Star Tracker
- Passive Optical Terrain Relative Navigation (TRN)
- Surface and Low Lunar Orbit (LLO) Beacons

Of these sensors, the DSN update, IMU, NDL, and star tracker are common to all sensor suites compared in this section. The DSN update accuracy is varied in the study, unlike the performance of the IMU, NDL, and star tracker which have fixed statistical error specifications. This is done to assess the impact to landing dispersions of differing amounts of time spent tracking the spacecraft in LLO. In terms of operation, the DSN update is incorporated into the on-board navigation filter five minutes prior to the De-Orbit Insertion (DOI) burn start. Note that the trajectory used in this analysis initializes 60 minutes prior to DOI in a 100km x 100km circular LLO. DSN state estimation accuracies were taken from an ALHAT study conducted in 2006 by Emil Schiesser[4].

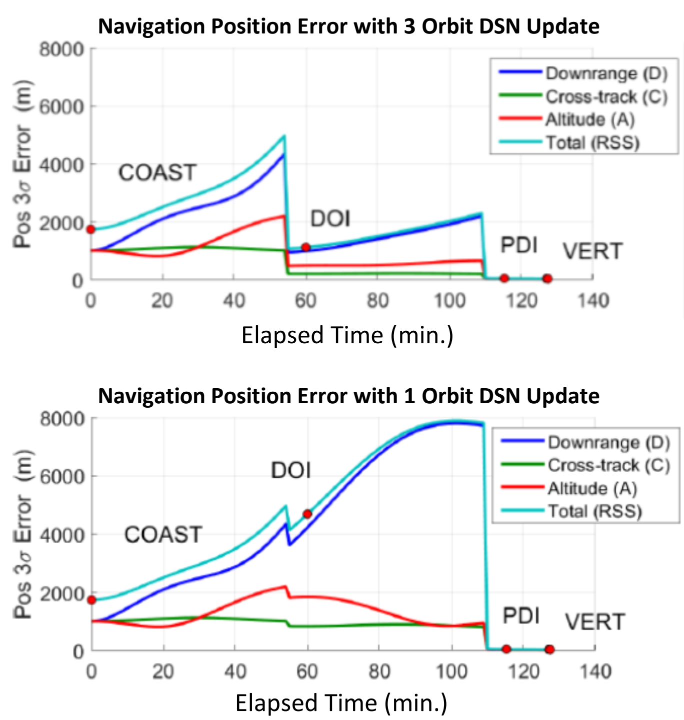

Figure 2: DDL Navigation Position Knowledge for 1 and 3 Orbit DSN Cases

The improvement in navigation state knowledge for the 1 and 3 orbit DSN tracking cases are clearly shown in Figure 2 at ~55 minutes into the trajectory. Because the plots of Figure 2 correspond to a sensor suite containing passive optical TRN operating from 1.5 km to 15 km, state knowledge is seen converging to better than 100m accuracies prior to Powered Descent Initiation (PDI). Table 1 shows the impact of 1 to 3 orbits spent tracking the vehicle in LLO on delta-v expenditure dispersions and trajectory dispersions at PDI. The results in Table 1 show that with a passive optical TRN system coming on at 15km altitude, touchdown accuracy is within 100m and independent of LLO DSN tracking performance. With the lighting conditions of the current DRM, it seems unlikely that passive optical TRN will be available at those altitudes. Thus, the accuracies shown would likely be unachievable for systems dependent on passive TRN and DSN updates alone. However, the results in Table 2 give insight into how beacons can be used to improve landing accuracy with or without TRN.

Table 1: DDL Dispersions with TRN and without Beacons

GN&C PERFORMANCE METRICS	TD Rel Navigation Errors (3s)			TD Rel Trajectory Dispersions (3s)			PDI Rel Trajectory Dispersions (3s)			Delta-v Disp (3s)
Sensor Suite	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	DnRng (m)	CrTrk (m)	Alt (m)	Disp (m/s)
Case #2: DSN 3-Orbits + TRN + NDL	29	0.21	0.042	29	0.25	3.463	2412	199	631	4.49
Case #3: DSN 2-Orbits + TRN + NDL	29	0.21	0.042	29	0.25	4.183	6429	695	960	10.37
Case #4: DSN 1-Orbits + TRN + NDL	29	0.21	0.043	29	0.25	4.470	7592	817	984	12.15

Table 2: DDL Dispersions with Beacons

GN&C PERFORMANCE METRICS	TD Rel Navigation Errors (3s)			TD Rel Trajectory Dispersions (3s)			PDI Rel Trajectory Dispersions (3s)			Delta-v Disp (3s)
Sensor Suite	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	|Pos| (m)	|Vel| (m/s)	|Att| (deg)	DnRng (m)	CrTrk (m)	Alt (m)	Disp (m/s)
Case #12: DSN 3-Orbits + Surface Beacon	214	0.87	0.062	216	0.87	140.5	2412	199	631	23.23
Case #13: DSN 3-Orbits + Surface Beacon + Orbiting Beacons (LLO)	57	0.10	0.037	58	0.51	21.90	812	105	330	3.59
Case #14: DSN 3-Orbits + Surface Beacon + TRN	24	0.23	0.045	24	0.25	3.467	2412	199	631	4.21

For case 12 in Table 2, a single surface beacon located 2km cross-track from the landing site was assumed to provide range measurements to the vehicle while in sight. For case 13, an orbiting beacon in LLO was added to the sensor suite, also providing range measurements while in the vehicle's line of sight. Neither case 12 nor 13 were provided with TRN measurements. The target relative landing accuracies of the single beacon (214m) versus dual beacon (58m) imply that at least two beacons at different locations are needed to meet landing requirements (<100m). Note that having adequate time spent in the line-of-sight of the beacons is important. Finally, case 14 demonstrates that the addition of a surface beacon to a system supported by TRN slightly improves landing accuracy (from 29m to 24m).

As a result of this investigation into beacons and landing accuracy, it is apparent that beacons can alleviate the need for a passive optical TRN system, or at the very least provide essential navigation data prior to the TRN system acquiring accurate measurements near the landing site and in good lighting conditions. It was found that at least two beacons at different locations are needed to provide the state knowledge necessary to accurately land the vehicle without TRN. In all this analysis, it should be noted that beacon coverage and location play a key role. The next section will demonstrate how surface beacon location impacts landing accuracy.

Beacon Placement Analysis for Precision Landing

In the previous section, results were presented that assumed a surface beacon in a near optimal location for the reference trajectory's landing site approach direction (Table 2). However, the optimal surface beacon location for one approach is not necessarily the optimal location for an approach from a different direction. This section aims to demonstrate how surface beacon location relative to the approach trajectory of a lander effects landing accuracy.

In a 2008 study conducted by Christensen and Geller[2], a linear covariance approach similar to the one used in the previous section was used to assess landing accuracies with single and multiple surface beacons located at different locations up-range from the landing site and off-track from the approach. Of note is that this study also included assessments of landings with orbital beacon assets providing measurements, including orbital beacon geometry and phasing studies. However, of most interest here may be the single surface beacon landing case, which shows the sensitivity of landing accuracy to surface beacon location most clearly (Table 4).

Table 3: Duration of Beacon Visibility vs Beacon Location

Duration of Visibility (sec)		Off-Track Location of Beacon (km)											
		80	72	64	56	48	40	32	24	16	8	0	
Up-Range Location of Beacon (km)	0	0	0	0	0	0	0	0	0	58	100	221	1
	35	0	0	0	0	0	39	74	95	108	116	119	2
	70	0	0	0	0	53	76	91	102	110	113	115	3
	105	0	0	0	46	69	83	94	101	107	110	111	4
	140	0	0	29	56	73	85	93	99	103	105	107	5
	175	0	0	39	59	72	83	90	95	99	101	102	6
	210	0	0	42	60	71	80	87	91	94	96	97	7
	245	0	8	43	58	68	72	76	87	89	90	90	8
	280	0	13	41	48	64	68	71	83	85	86	86	9
	315	0	10	40	47	62	65	78	80	82	83	83	10
	350	0	10	30	50	60	64	77	79	80	81	81	11
		1	2	3	4	5	6	7	8	9	10	11	

Table 4: Landing Accuracy (meters) vs Beacon Location

Landing		Off-Track Location of Beacon (km)											
		80	72	64	56	48	40	32	24	16	8	0	
Up-Range Location of Beacon (km)	0									8	6	70	1
	35						12	10	9	8	9	567	2
	70					15	14	13	12	12	14	504	3
	105				20	18	17	17	17	17	20	437	4
	140			25	23	22	21	21	21	22	26	381	5
	175			28	27	26	25	25	26	27	32	337	6
	210			32	30	30	30	30	30	31	38	302	7
	245		51	36	35	34	34	34	35	36	43	274	8
	280		42	40	40	39	39	39	39	41	48	252	9
	315		46	44	44	43	43	43	44	46	54	235	10
	350		51	50	48	48	48	48	49	50	59	221	11
		1	2	3	4	5	6	7	8	9	10	11	

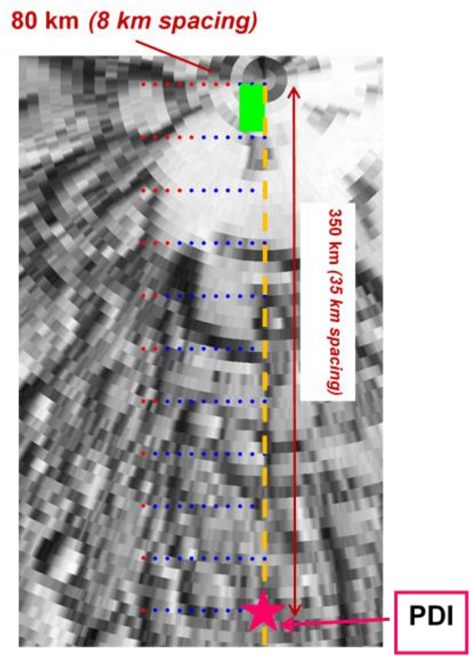

Figure 3: Beacon Coverage Map

In Table 3 and Table 4, the up-range and off-track beacon locations on the surface of the Moon are shown in Figure 3. Blue dots indicate beacons that have line of site to the lander, red dots indicate beacons that do not. It is readily apparent from Table 4 that single beacons with no off-track displacement from the vehicle approach are undesirable. Because there is little off-track displacement to the beacon, off-track components of state uncertainty are not corrected effectively by the beacon ranging measurements. Of note in is that total durations of beacon visibility increases as the surface beacon is placed closer to the landing site. This is due to reduction in the planet relative speed of the lander as it approaches the landing site. However, the increase in duration of visibility doesn't tell the whole story. A beacon placed up-range from the landing site provides benefits in that it can be visible prior to PDI, as shown in Table 5.

Table 5: Position Uncertainty at PDI vs Beacon Location

PDI	Off-Track Location of Beacon (km)											
Up-Range Location of Beacon (km)	80	72	64	56	48	40	32	24	16	8	0	
0									1525	1495	1436	1
35						1651	1611	1572	1541	1522	1431	2
70					1696	1659	1620	1585	1559	1554	1418	3
105				1735	1701	1664	1627	1595	1577	1586	1405	4
140			1773	1743	1709	1672	1637	1608	1599	1620	1402	5
175			1780	1750	1716	1681	1647	1623	1625	1641	1403	6
210			1787	1756	1723	1689	1659	1641	1653	1624	1408	7
245		1821	1793	1762	63	64	66	71	81	122	304	8
280		1826	62	62	52	53	55	51	60	92	276	9
315		51	50	49	47	47	48	50	57	85	256	10
350		52	50	44	44	43	44	46	52	78	238	11
	1	2	3	4	5	6	7	8	9	10	11	

Rows 1–7: Beacon not visible prior to PDI

Rows 8–11: Beacon visible prior to PDI

The increased state knowledge at or near PDI that an up-range surface beacon provides translates into powered descent delta-v savings.

An important caveat about the Christensen and Geller[2] study is that the results they present are highly trajectory dependent. Trajectories that approach the landing site at shallower or steeper angles, or that conduct PDI closer to or further from the landing site, may have different sensitivities to surface beacon off-track and up-range locations. However, the following trends should hold for most landing trajectories. First, an off-track component of surface beacon location of at least 2km is required to constrain drift in off-track navigation error. Second, placing the beacon up-range from the landing site can provide valuable navigation state knowledge earlier in the approach, translating to delta-v savings. Finally, placement of additional beacons at different surface locations can further improve navigation performance.

Low Lunar Orbit State Knowledge with Beacons

Another challenge for navigation requirements has been gathering essential observations in LLO. The government reference mission currently baselines three revolutions in LLO, which, with observations from sources like the DSN, allows the navigation state knowledge to be accurate enough to begin deorbit, descent, and landing. However, it is important to consider reducing reliance on ground tracking from heavily utilized sources like the DSN. Further, because loiter time in LLO reduces surface stay time at a one-for-one ratio, there are overall mission timeline benefits to reducing this coast time. By supplementing or replacing sensor suites and DSN observations, beacons could simultaneously reduce reliance on the DSN and increase surface stay time by reducing required LLO loiters.

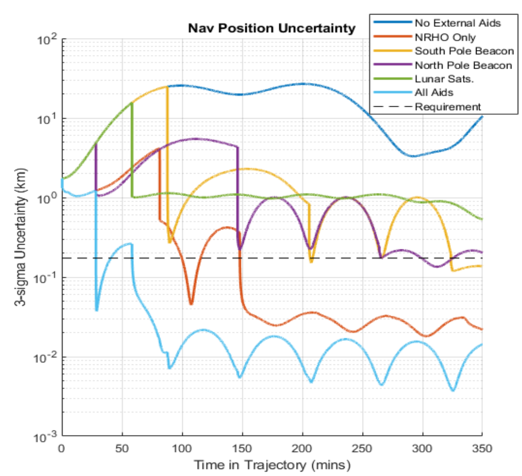

Figure 4: Navigation Position Uncertainty over LLO Coast

To determine how Beacons can support and the optimal locations to support LLO Navigation, navigation position and velocity uncertainties are determined for 3 revolutions in the reference LLO (100x100km). Beacons in this study are placed in various locations including the government reference NRHO, LLO (polar and equatorial), and the surface at the north and south poles. A covariance analysis assessing state knowledge uncertainty is performed.

Figure 4 and Figure 5 show the resulting navigation position uncertainty and velocity uncertainty in the LLO, respectively. A beacon in NRHO is found to have the greatest support of LLO state knowledge, due to its near planar alignment and long observation times of the LLO being utilized. Surface beacons at the poles do not provide as beneficial of support of the LLO state knowledge, due to limited observational ability of less than one half rev. It should also be noted that these polar surface beacons performance would further be reduced if alternative, non-polar LLO is utilized on a sustained mission.

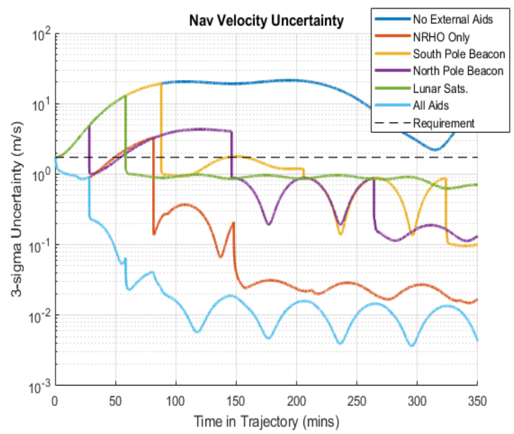

Figure 5: Navigation Velocity Uncertainty over LLO Coast

Implementation

There are currently outlined S-band, two-way ranging interfaces and specifications for HLS to follow in regards to applications like RPOD with Gateway and ground operations. Implementations of beacons can leverage these already existing configurations in addressing navigation needs. Selected references that outline these standards are listed below in Table 6.

Table 6: Applicable HLS Interface and Specification Documents

Document #	Document Title
HLS-IRD-001	GW VV IDD HLS Interface Requirements Annex
GP 10010	Gateway Docking Systems Specification (GDSS)
GP 10013	Gateway Program Specification for Guidance, Navigation and Control (GNC)
GP 10031	Gateway To Visiting Vehicle Interface Requirement Document

While Table 6 focuses on already addressed solutions, other methods of communication standards like CDMA S-band signals or MAPS are under development. Expansion of beacon implementation to these standards can be considered in future sustained applications. These can include time-based communication ranging like Multi-spacecraft Autonomous Positioning Systems (Anzalone et al., 2020) and CDMA S-band signals similar to GPS-like data for one-way.

Summary

Prior analysis outlined in this white paper has shown that beacons have significant application in supporting navigation requirements related to landing precision and in-space state knowledge. In comparison to technology like passive TRN, beacons do not require lit trajectories to support precision landing. This eases landing site and landing epoch limitations, especially in polar regions. Further, beacons can supply addition observation sources to reduce required time LLO. Less time in LLO alleivates the mission timeline in a way to increase valueable surface stay time for the sortie. Lastly, beacons also supply a source of navigation observations, for in-space and descent applications, independent of Earth based assets like DSN, allowing supplemental observations and autonomy from these already heavily utilized resources.

References

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[4] Schiesser, E. (2006, March). CEV Navigation Sensor Suite Preliminary Design. EG-CX-06-2.