Catenary Model of InSight SEIS Tether for Instrument Deployment

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***Abstract*—NASA's InSight Mars Lander, which landed on Mars in November 2018, completed the first precision robotic instrument placement on a planetary surface as part of its instrument deployment phase. Using the Instrument Deployment Arm (IDA), InSight deployed the two key science payload elements, a seismometer (SEIS) and heat flow probe (HP3), as well as a wind and thermal shield (WTS) placed over the seismometer. SEIS and HP3 are tethered to the lander for both power and communications purposes. Placement accuracy of the instrument deployment was essential for successful realization of the mission's core science objectives. In order to meet the requirements for placement accuracy, we worked to understand and mitigate the factors contributing to placement error. Those factors include but are not limited to: the IDA position control error, the error in the computation of the digital elevation model (DEM), the targeting error in selecting the desired placement site, and each instruments ground interaction.**

In particular, the SEIS placement accuracy was greatly affected by the placement of its tether on the terrain during the instrument deployment. The SEIS tether is a stack of six flex cable belts attached at one end to the lander deck. At the other end, the tether is looped and attached to the instrument with a load shunt assembly (LSA) designed to isolate signals detected by the instrument from any noise created by the tether due to thermoelastic deformation, atmospheric events, etc. Additionally, the tether contains a field joint and a pinning mass (which grounds the tether and is used to manipulate the tether with the robotic arm post-placement). In our validation and verification (V&V) activities, we determined that the interaction of the SEIS tether on the terrain greatly affected our instrument placement accuracy. In order to understand and minimize this effect, we created a mathematical model of the SEIS tether and then used that model to develop the deployment sequences. Ultimately, our sequences deployed both the tether and the instrument on the Martian surface, taking into consideration the whole system for a successful deployment.

This paper will discuss the motivation and details of the implementation of the SEIS tether model and the ways in which the SEIS tether impacted placement accuracy in certain configurations. It will also show results from testing this model on Earth and deploying SEIS to the Martian surface on sol 22 of InSight's mission.

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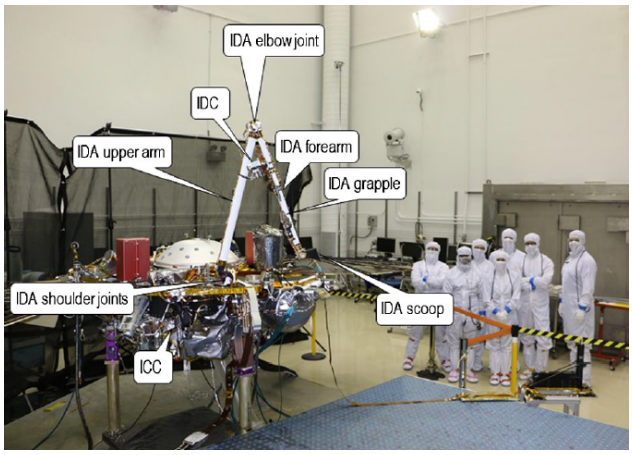

Figure 1. Instrument Deployment System in ATLO at Lockheed Martin [3]

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1. INTRODUCTION

The Instrument Deployment System

InSight's Instrument Deployment System (IDS), as seen in Figure 1 consists of the Instrument Deployment Arm (IDA), Instrument Deployment Camera (IDC) mounted on the robotic arm, and the Instrument Context Camera (ICC) mounted on the lander. Additionally, the IDS includes the motor controllers, a five-finger grapple, and a scoop. The Instrument Deployment System is responsible for the first-ever deployment and release of science instruments on a planetary surface [3].

Figure 2. The SEIS (and its tether) deployed in ATLO at Lockheed Martin [4]

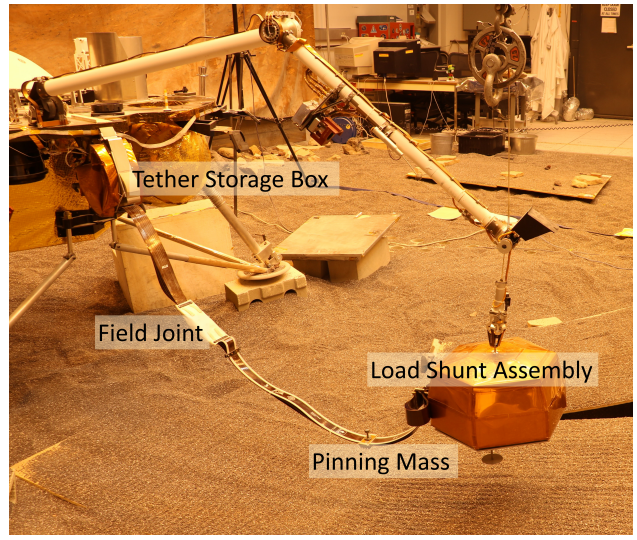


Figure 3. SEIS and tether deployment in testbed, with components labeled

The two instruments deployed to the Martian surface are a six-axis seismometer, SEIS, [4] and a heat flow and physical properties package, HP3 [5]. Successful deployment of these instruments was essential for the InSight mission to meet its science goals. The instruments were deployed by the IDA using the grapple.

InSight Mission Requirements and Design

Mission requirements for instrument placement at a desired target on the Martian surface were defined to consider the several factors, including the following:

- Horizontal placement accuracy
- Slope of instrument foot plane
- Tilt of lander

For mission operations, SEIS deployment is broken down into 4* major components, each with a ground-in-the-loop where the operations team received data back from Mars and made a 'Go' decision to proceed with nominal deployment operations[3]. These components occurred on separate sols:

1. Move robotic arm to teach point where grapple is just above SEIS grapple hook
2. Grapple SEIS
3. Place SEIS on Martian surface
4. Release SEIS (*preceded by grapple adjustment if necessary, considered 4a)

To successfully deploy the seismometer on the Martian surface, the team needed to consider the dynamics of the entire instrument system, which included its tether. This paper focuses on strategies and tools developed for Part 3 of SEIS deployment (Place SEIS on Martian surface), which lifts SEIS from the lander deck, peels the tether that is attached to the lander by Velcro, swings SEIS over the workspace, and places the instrument down on the Martian surface. Figure 2 shows the seismometer deployed on the floor of the ATLO facility at Lockheed Martin Space Systems in Litteton, CO.

SEIS Deployment Concepts

In this paper, we are focusing on a few key components of the SEIS tether system as seen in Figure 3: the Tether Storage Box (TSB), the Field Joint (FJ), the Pinning Mass (PM), and the Load Shunt Assembly (LSA)[4]. While the SEIS was on the deck of the lander, the tether was attached to the deck using Velcro. During SEIS deployment (part 3 above), the robotic arm lifted SEIS up and across the lander deck to peel the tether off of the deck in a smooth motion. Once the tether is peeled, the tether hangs from two points: one point at the exit of the Tether Storage Box mounted on the lander, and the other point at the Load Shunt Assembly loop where it attaches to the instrument. It is at this point that the tether takes on the catenary shape, and our quasi-static model is interpreted to help us predict the position of the pinning mass and the field joint along the tether as we move the SEIS away from the lander and over the terrain.

When deploying SEIS in the deployment testbed and with the flight hardware, the team determined that the configuration of the tether had a significant impact on the SEIS instrument placement accuracy. For example, if the SEIS deployment target was close enough to the lander, the pinning mass generally touched the ground before the SEIS. In this case, it acted as an anchor for the tether, which behaved like a stiff spring and pushed SEIS out further from the lander in the radial direction. Additionally, if the arm is fully outstretched and the SEIS placement target is past a certain radial distance, the stiff tether would pull the SEIS in closer to the lander in the radial direction.

After observing these effects, the team decided to develop a model to predict which part of the tether would touch the terrain first, given knowledge of the height of the terrain from the lander to the desired deployment target. By modeling the tether height throughout the deployment trajectory, we could control the deployment of the tether itself and utilize the tether-terrain interactions to our advantage. We chose to use a catenary equation rather than an arbitrary polynomial equation for the ease of computation, verification, and implementation in our simulation and visualization software. Additionally, the tether's stiffness and bending behavior as discussed in Section 3 made it unlikely that we could use a single polynomial equation across the entire deployment workspace.

2. CATENARY MODEL

Key Concepts

In deploying our payloads, we commanded the robotic arm to a series of waypoints, each followed by a set of images with the IDC and ICC. During the deployment sequence, the arm (and the payload) remain still during the duration of the image acquisitions (roughly 1.5-2 minutes) before moving on to the next commanded position. By choosing to model the tether and solve the equation at these specific configurations along the trajectory of SEIS deployment, we took a quasi-static approach and ignored inertial effects. This simplified the problem while still remaining relevant for understanding the movement and position of the tether during deployment.

A cable hanging from two supports will take the shape of least potential energy, which is a hyperbolic cosine, also known as the catenary curve. A catenary is a flexible, inelastic tether hanging from two supports under its own weight. It is of uniform density with uniform tension acting tangentially along the curve [1], [2].

To use the static catenary equation to model the SEIS tether, we noted some key assumptions:

- A catenary is suspended from two points in the same horizontal plane with only tangential forces acting along it.
- A catenary has uniform mass per unit length.
- A catenary is so thin that it can be represented as a 2D curve.

Physical Properties of SEIS System

The above assumptions idealize the physical properties of the catenary. In this use case, many physical properties of the SEIS tether do not conform to these assumptions. Ultimately, assuming these ideal properties allowed us to create a piece-wise linear model that represented the tether configuration with enough accuracy for the purpose of predicting when and where the tether would contact the terrain, which was our ultimate goal.

The SEIS tether does not have uniform mass per unit length due to the field joint and the pinning mass along the SEIS tether as well as the use of Velcro along part of the tether. However, the masses of the field joint, the pinning mass, and the Velcro were negligible compared to the mass of the overall tether system. Additionally, the SEIS tether has a non-negligible thickness and stiffness. The structure of the tether is not like the idealized chain/string; it is 5.08 cm wide, has Velcro along it, and has some stiffness that we have attributed to it being attached to the lander for a long period of time. Throughout the life of the mission up until deployment, from the launch stow of the tether and instruments, the tether experienced many different thermal conditions: launch, cruise, entry, descent, and landing, and surface day/night cycles in its stowed configuration. Finally, we had to convert our 3D problem (with position data in the X, Y, and Z dimensions) to a 2D problem (R, Z) to solve for the static catenary at each point, where $R = \sqrt{X^2 + Y^2}$. By choosing to idealize the tether's 3D structure and solve for the 2D catenary, we achieved a model that was usable in predicting tether height above the terrain and could additionally be converted back to 3D for a prediction of the horizontal position of the pinning mass and field joint.

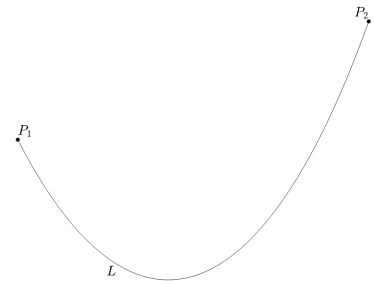


Figure 4. Catenary curve between two points

Solving the Equation

$$V = x\cosh(\frac{(x_S - a)}{x}) - x\cosh(\frac{(x_T - a)}{x}) \quad (1)$$

$$L = x\sinh(\frac{(x_S - a)}{x}) - x\sinh(\frac{(x_T - a)}{x}) \quad (2)$$

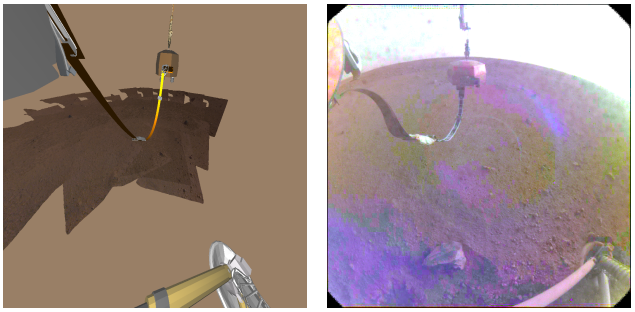
In this equation, the length of the tether, L, and the position of the tether attachment point to the lander, x_T, are known and constant (provided that we know the tilt of the lander relative to gravity). For each pose of the dangling SEIS in the deployment trajectory, the location of SEIS, and therefore the attachment point of the tether to SEIS, x_S, can be estimated, given the position accuracy of the arm and the angle of SEIS tilt in midair (due to the tether's weight). From there, we can compute the position of the points on the tether, where V is the vertical distance between the two ends of the catenary, P_1 and P_2. P_1 is defined as the point where the tether exits the TSB and is computed based on lander tilt and its position relative to the IDA frame origin (at the base of the robotic arm's azimuth joint). P_2 is defined as the point where the tether attaches itself to the LSA and is estimated based on the position of SEIS and the geometry of SEIS and the LSA, with this attachment point presumed to be within certain bounds due to the arm's position error ellipse.

$$P_1 = [X_{TSB}, Y_{TSB}, Z_{TSB}] \quad (3)$$

$$P_2 = [X_{SEIS}, Y_{SEIS}, Z_{SEIS}] \quad (4)$$

$$V = Z_{SEIS} - Z_{TSB} \quad (5)$$

Solving the equations (1) and (2) in this way provided us with an estimate for the position of the entire tether. We chose to focus on three points and their relation to the Martian surface: the position of the field joint, the position of the pinning mass, and the lowest point on the tether. For example, it was a desirement that the field joint and pinning mass touch the surface on areas clear of large rocks or holes. Additionally, it was a requirement that there be no rocks under the LSA that could inhibit its ability to open fully. Finally, we were able to predict when the pinning mass would touch down in relation to the SEIS. We effectively controlled the placement of the pinning mass on the surface and used the interactions with the terrain to our advantage in deploying as closely as possible to our desired target, in tests on Earth and on the Martian surface.



(a)RSVP simulated ICC view (b)Actual ICC View

Figure 5. SEIS Deployment: Tether catenary model (a) vs reality on Mars (b) of one waypoint in deployment trajectory

3. SEQUENCING SEIS DEPLOYMENT

RSVP Implementation

The IDS team uses the Robot Sequencing and Visualization Program (RSVP) and the Robot Sequence Editor (RoSE) to develop and simulate commands and sequences before running full simulations with the spacecraft flight software, running sequences in the testbed at JPL, and commanding the lander on the surface of Mars. Terrain meshes created from the DEM products described in [9] are loaded into RSVP and used to simulate sequences that involve interacting with the terrain such as instrument deployment, soil experimentation, and imaging sites of geologic interest [6], [7]. The RSVP team implemented the quasi-static catenary model shown in Figure 4 and represented by equations (1) and (2) to visualize the SEIS tether when SEIS is grappled and above the terrain. During simulation of deployment commands and sequences, the placement of SEIS, the tether itself, and the locations of the pinning mass and field joint on the tether could be visualized in relation to the terrain height during all poses of the deployment (as seen in Figure 9). This aided the team in modifying the commanded trajectory for SEIS deployment based on the terrain properties to better control the tether's effect on the overall placement of SEIS.

Use in Validation and Verification Activities

In order to validate that our system met requirements developed for instrument deployment, we deployed the SEIS in the testbed as well as in ATLO in a variety of configurations including different lander tilts, workspace configurations, and deployment position targets. Alongside these tests, the tether catenary model was used to develop the SEIS deployment sequences used in each test. The position of the tether was computed at a few key points along the deployment trajectory to determine whether the tether was at risk of making early contact with the surface and whether the SEIS or the pinning mass would make contact first, etc. Additionally, RSVP implementation of the tether catenary model with models of the terrain slope and height at the deployment position targets allowed for more rapid iteration during sequence development and preparation for these V&V activities.

Validating the Model

To test the accuracy of our model and determine its usefulness in deploying SEIS, we used the InSight deployment testbed at the Jet Propulsion Laboratory. The testbed is comprised of a lander mockup, the engineering model of the IDA with its motor controllers, and weight models of the deployable payloads. In order to compare the tether pose estimates from the catenary model to experimental results, a Vicon motion capture system allowed us to measure the position of points along the tether, such as the pinning mass and the field joint, as seen in Figure 6.

Figure 6. **Testbed setup with Vicon markers placed to measure position of tether**

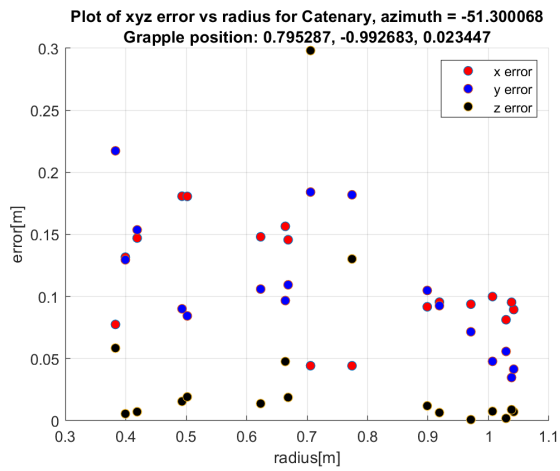


Figure 7. **Sample result from comparing catenary model with Vicon measured points along tether curve**

We grappled SEIS with the IDA and commanded the arm to 15 unique poses at varying heights, radial distances, and azimuths within the workspace. We used Vicon to measure the position of the field joint and pinning mass and then compared these results to the model's estimates. We performed a sensitivity analysis to determine whether the errors in the x, y, and z dimensions of the tether model compared to our testbed tether were affected by either the SEIS's radial distance from the lander or the azimuth angle of the robotic arm in relation to the azimuth angle of the tether storage box configuration.

Figure 7 shows a dataset collected for one of the 15 unique poses of the robotic arm with SEIS and tether outstretched. For this specific position, it is clear that the horizontal (X and Y) errors in the model are much higher than the vertical (Z) error. We have found that this is consistent across datasets collected at a variety of large negative azimuth angles.

Ultimately, this sensitivity analysis provided us with critical information about the characteristics of the error in the model compared to the experimental results. We were able to see

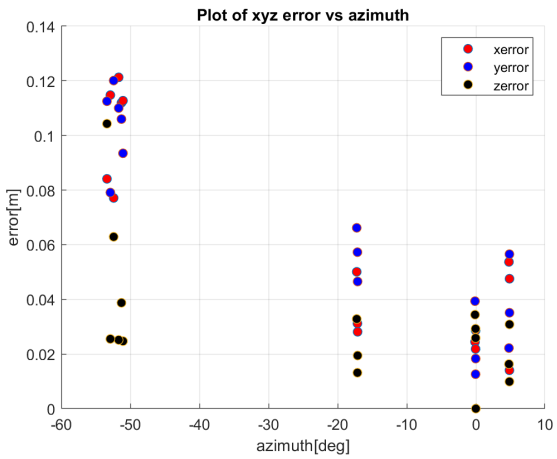


Figure 8. Composite plot of mean error in X, Y, and Z directions at varying azimuths

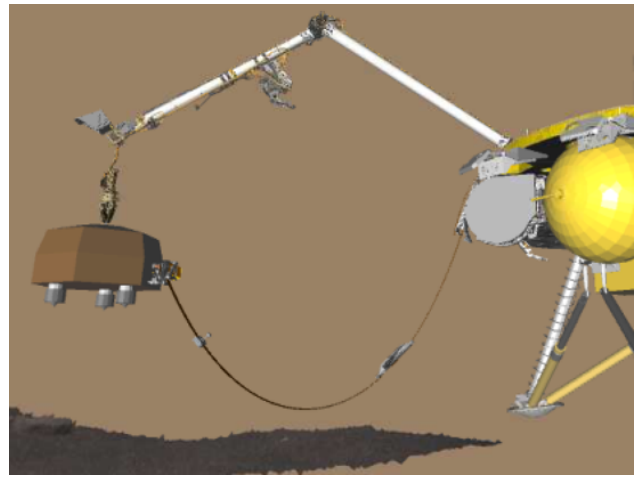


Figure 9. RSVP simulation with suspended SEIS tether catenary over terrain mesh

that the horizontal error was increased at large negative azimuth angles, which is consistent with the observation of the tether bending as it exits the tether storage box due to its width and stiffness. The tether storage box is oriented at an angle of about +15 degrees from the IDA origin. At deployments with a negative azimuth angle, the tether bends much more significantly, which decreases the horizontal accuracy of the model in that configuration. The overall preference for SEIS deployment locations was generally in the positive azimuth direction, so we were able to accept the modeling error at high negative azimuths with the knowledge that we likely would not deploy to that location. We considered an acceptable error bar for the horizontal error to be $\pm$ 5cm, or about the full width of the tether itself. The vertical error was consistently much smaller than the horizontal error across the entire workspace. The error in height of the tether model over the terrain compared to the actual height of the tether was consistently below 2.5cm, which gave us confidence in using the catenary model to predict the area of the tether closest to the terrain at the crucial waypoints in the trajectory of the deployment.

4. Surface Operations

Instrument Site Selection Working Group (ISSWG) Analysis

After landing, unstowing the robotic arm, and imaging the instrument deployment workspace with the IDC across several sols, the InSight team processed Digital Elevation Models (DEMs) on the ground to create workspace mosaics for use in the Instrument Site Selection Working Group (ISSWG) [10]. The ISSWG team used these workspace mosaics and additional products created from the DEM data [9] to select sites for SEIS and HP3 deployment based on engineering and science requirements and criteria to ensure safe deployments and optimal instrument performance [8]. The specific requirements and desirements for the SEIS deployment site can be found in [4]. Selection criteria included details about the terrain (such as the slope of the terrain, the number and size of rocks in the region and assumed load-bearing properties of the regolith) and distance between the SEIS and both the lander and the desired site for the HP3.

Selection of a viable deployment site for the SEIS instrument included consideration of the tether and its components. The slope of the terrain between the lander and SEIS was relevant as well as at the likely SEIS foot-plane, since the position of the tether on the surface impacts placement accuracy. The likely placement sites of the components of the SEIS tether, the field joint, pinning mass, and load shunt assembly were also considered: we selected sites free of rocks and other obstacles. In order to consider these requirements during the Instrument Site Selection process, we used the catenary model of the tether to assess the terrain at the potentially viable deployment sites for SEIS and the tether components. Using the catenary model and the DEM in RSVP, we could visualize the tether and its components over the terrain and predict whether the pinning mass, field joint, and SEIS would touch down on regolith with favorable properties that met the ISSWG requirements and desirements. While simulating each command in the sequence, we could check the terrain below the key components of the tether. After these simulations, we deployed SEIS in the testbed with a terrain that was sculpted to match the DEMs generated to represent the surface of Mars, verifying that our model provided correct intuition about the tether-terrain interactions and its effects on SEIS placement.

Deploying SEIS on Mars

On sol 22, we deployed the SEIS onto the Martian surface. See Figure 11 for a post-deployment view of the Instrument Context Camera.

The deployed SEIS tether on the surface of mars matched the predicted catenary model. The team determined that the deployed SEIS was in a favorable configuration and proceeded with surface operations. After SEIS deployment, we adjusted and released the grapple and conducted a post-placement imaging campaign to assess the state of the instrument, the LSA, and the tether. Figure 12 shows the state of the tether on the surface after deployment.

Ultimately, the successful deployment of SEIS led to the first observations of seismic activity on Mars as described in [11].

5. Conclusion

The Instrument Deployment Systems team developed algorithms and tools that successfully managed the tether-terrain

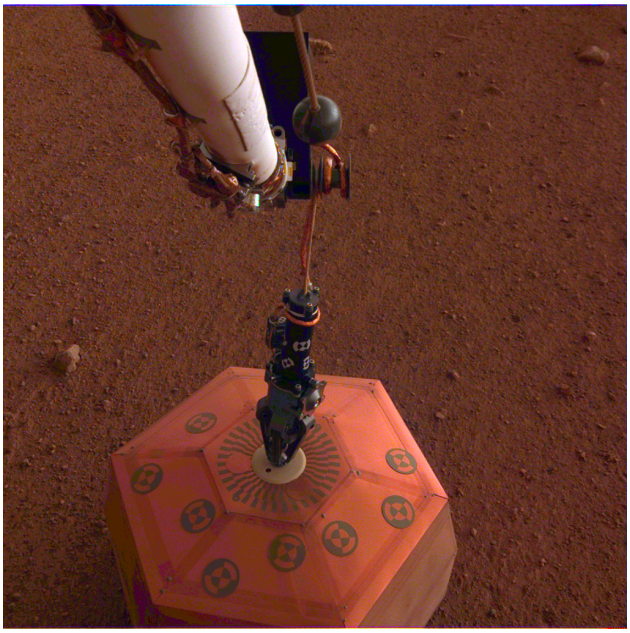


Figure 10. **IDC view of deployed SEIS from sol 22.**

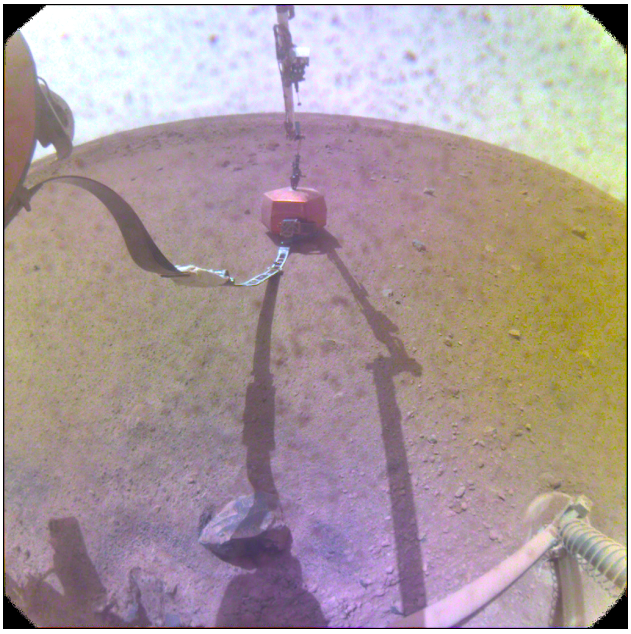


Figure 11. **ICC view of deployed SEIS from sol 23. The pinning mass is in contact with the regolith**

interaction during the extremely complex deployment of the InSight Seismic Experiment for Interior Structure (SEIS). We designed, developed, and tested the first-ever catenary model for a payload with a long, stiff tether connected to a lander and held by a robotic arm with a free-hanging grapple. The novel catenary model usage incorporated the IDS workspace terrain topography, lander tilt, payload orientation, and robotic arm pose to provide trajectories for mission operators to follow as they use the IDS to place payloads on the surface of Mars. In addition, the catenary model enhanced mission safety by simplifying tactical sequence development. The catenary model enabled the IDS team to evaluate several thousands of payload deployment scenarios in simulation, conduct early risk-reduction activities, and

Figure 12. **Processed mosaic of tether on sol 26**

evaluate performance of key design elements for the SEIS deployment.

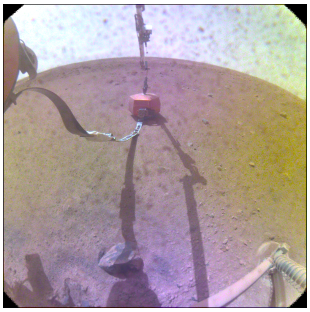
It is imperative that future missions calling for instrument deployment and release consider the deployment of each instrument subsystem, including tethers and any other attached components, in the mission architecture and design of requirements and operations planning. InSight's Instrument Deployment phase was a success thanks to the hard work of the entire InSight mission operations team. The interior structure of Mars is slowly being uncovered as the seismometer collects data on the Martian surface. The InSight science team is hard at work analyzing the data and interpreting the results.

ACKNOWLEDGMENTS

We would like to thank the Instrument Deployment Systems team and the Testbed team for their assistance in testing the model: Nythi Udomkesmalee, Pranay Mishra, and Marleen Sundgaard.

Additionally, we would like to acknowledge the contributions

(a)RSVP simulated ICC view



(b)Actual ICC View

Figure 13. SEIS Deployment: Tether catenary model (a) vs reality on Mars (b) after SEIS placed on surface

of the RSVP development team for the implementation of the tether model: Jeng Yen, Amanda Chung, Mohith Manohara, Kaitlyn Biesiadecki, and Stephen Decker.

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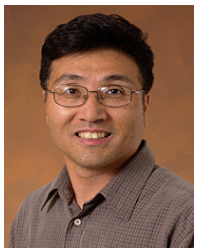
BIOGRAPHY

Cristina Sorice *has an B.S. and M.S from the University of Pennsylvania and joined the NASA Jet Propulsion Laboratory in 2015. As part of her role on the InSight mission, she has served as a Robotics Engineer for the InSight lander, contributing to VV, ATLO, and surface operations for the robotic arm and two cameras. Cristina led the deployment of HP3 and was a core member of the Anomaly Response Team for the HP3 mole anomaly. While at JPL, she has also worked on autonomous aerial vehicles, multi-agent systems, and now writes controls and autonomy software for Mars Science Helicopter.*

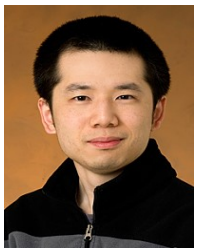
Philip Bailey *graduated with a B.S. and M.S. from Carnegie Mellon University and joined the NASA Jet Propulsion laboratory in 2015. After coming to JPL he originally worked as a robotics engineer on autonomous motion planning software for unmanned surface vehicles. On InSight, Phil worked on the Instrument Deployment Team, which was responsible for the instrument deployment arm and both cameras. Before launch, he contributed to the testbed VV and ATLO campaigns. After launch he worked on the operations team as a robotic arm operator and was responsible for the localization of the deployed payloads. After InSight Phil has been working on the Mars 2020 Rover with the Flight Systems team supporting the Robotic Arm.*

Dr. Ashitey Trebi-Ollennu *, FIET, FRAeS, SMIEE,PMP, FGA, is a Principal Engineer, Chief Engineer of Mobility and Robotics Systems Section, and a group supervisor of Robotics Systems Staff at JPL, where he has been since 1999. Dr. Trebi-Ollennu was the Project Delivery Manager (PDM) for InSight's Instrument Deployment System (IDS) and the IDS operations Team Chief with overall responsibility for successful operation of IDS.*



Dr. Won S. Kim *received his Ph.D. in electrical engineering and computer sciences from the University of California, Berkeley, in 1986. Since 1988, he has been in Jet Propulsion Laboratory. In 2009, he received NASA Exceptional Engineering Achievement Medal for the successful maturation, validation, and deployment of the Visual Target Tracking capability. He is currently robotics system engineer for the InSight Project and robotic system*

analyst for the Sample Handling Assembly (SHA) of Mars 2020.



Steve Myint *received his B.S. in computer science at Cal Poly Pomona. He led the development of the RSVP tool for InSight. He is currently developing flight software for the Mars 2020 rover, applying modern software fuzzing techniques to finding problems in safety critical flight software, and leading the development of the primary simulation tool for Mars 2020 rover operations.*