Hayabusa2 Touch-down to Ryugu with Onboard Guidance Sequence Program

Seiji Yasuda[a]* and Toshio Kamiya[a]

[a] *Space Systems Division, NEC Corporation, Nisshin-cho, Fuchu, Tokyo, Japan, 183-8551,* yasuda_sj@nec.com
* Corresponding Author

Abstract

The asteroid explorer Hayabusa2 was launched by Japan Aerospace Exploration Agency (JAXA) on December 3, 2014. The main mission of the spacecraft is to sample material of Asteroid and return back to the Earth. Hayabusa2 has reached Ryugu in June 2018 and observed its geography by operations such as middle/low altitude observation and Touch Down rehearsal. Because of the rough terrain, we have to modify the Touch-Down (TD) operational design. Before reaching Ryugu, we planned to carry out dropping Target Marker (TM) and touching down to Ryugu as a single sequence of TD operation. However after finding the rough terrain, we have firstly carried out dropping TM and close-up observation around the TM as the first step of the TD event in October 2018. As a result of close-up observation, we have found the flat area around TM (about 3m) is narrower than the area we assumed (about 50m). Just after the TD, a large amount of dust were thrown up. As a result, the touch down sequence was needed to be changed because the performance degradation has occurred on navigation sensor such as navigation camera (ONC) and altimeter (LIDAR, LRF). Hayabusa2 has accomplished second TD after flexible sequence changes with on-board sequencer function called GSP (Guidance Sequence Program). This paper presents how the touch-down events have been carried out with on-board GNC system and operational design with the flight data of the second TD to Ryugu with GSP.

はやぶさ２ オンボード航法誘導則による Ryugu への高精度タッチダウン

摘要

2014 年 12 月 3 日 JAXA により打ち上げられた、小惑星探査機「はやぶさ２」は、2018 年 6 月に Ryugu に到達し、中低高度観測により、小惑星地形を観察した。その結果、当初想定していた半径 50m の平坦な地形は存在せず、TM 周辺のわずか 3m の領域にタッチダウンすることが求められた。また、1 回目のタッチダウンで巻き上げられたダストにより、光学カメラ（ONC）および高度計（LIDAR, LRF）の性能が劣化したため、2 回目のタッチダウンについても運用シーケンスの変更が求められた。はやぶさ２は、2 回のタッチダウンを GSP と呼ばれる機能により、フレキシブルにシーケンスを変更して達成した。

本論文では、はやぶさ 2 に搭載された航法誘導制御システムおよび GSP 機能を紹介するとともに、2 回のタッチダウンがどのように達成されたのか、軌道上データをもとに解説する。

Nomenclature

- $\bar{x}_k$: State variable (after time update)
- $\hat{x}_k$: State variable (before time update)
- u_k: Control vector
- $\bar{P}_k$: Covariance matrix
- Q_k: Covariance of process noise
- K_k: Kalman gain
- H_k: Observation model
- R_k: Covariance of observation noise
- z_k: Observation vector
- $\vec{r}_{SC/NT}$: Position of spacecraft at NT coordinate
- $\vec{v}_{SC/NT}$: Velocity of spacecraft at NT coordinate
- $g_{/NT}$: Asteroid gravity acceleration at NT coordinate
- $\Delta V_{/NT}$: Control vector at NT coordinate
- $\vec{r}_{LO/NT}$: Observation point for LRF at NT coordinate
- $\vec{r}_{CO/NT}$: Observation point for ONC at NT coordinate

Acronyms/Abbreviations

- Japan Aerospace Exploration Agency (JAXA)
- Small Carry-on Impactor (SCI)
- Touch-Down (TD)
- Guidance, navigation and control (GNC)
- Star tracker (STT)
- Inertial reference unit (IRU)
- Reaction control system (RCS)
- Reaction wheel (RW)
- Light detection and ranging (LIDAR)
- Optical navigation camera-W1 (ONC-W1)
- Target marker (TM)
- Flash (FLA)
- Laser range finder (LRF)
- GCP-NAV (Ground Control Point Navigation)
- Navigation target (NT)

Optical Navigation Camera Electric (ONC-E)
Charge Coupled Device (CCD)
Attitude and orbit control processor (AOCP)
Attitude control flight software (ACFS)
Guidance sequence program (GSP)
Command memory table (CMT)
Conditional branch table (CBT)

1. Introduction

The asteroid explorer Hayabusa2 was launched by Japan Aerospace Exploration Agency (JAXA) on December 3, 2014. The main mission of the Hayabusa2 is to sample material of Asteroid and return to the Earth [1] [2].

Hayabusa2 has reached Ryugu in June 2018 and successfully executed its first Touch-Down (TD) on February 22, 2019 to collect samples from the asteroid's surface, followed by its second on July 11 to collect samples from the subsurface caved by Small Carry-on Impactor (SCI). And finally, on December 6, 2020, Hayabusa2 has returned to the Earth with a large amount of sample of Ryugu.

Hayabusa2's autonomous guidance, navigation and control (GNC) system has contributed to two times TD with pinpoint precision with a margin of error of about 1m in the restrictions imposed by the asteroid's high-temperature environment and communication lag with operators back on Earth.

We present Hayabusa2 on-board GNC system in section2, how we realize the TD sequence with on-board GNC system in section3, and flight results of first and second TD in section4.

2. Hayabusa2 On-board GNC System

Fig. 1 shows an external view of Hayabusa2's autonomous navigation, guidance, and control system. As standard devices for navigation, guidance, and control, Hayabusa2 is equipped with a star tracker (STT) and an inertial reference unit (IRU) to estimate the attitude of the spacecraft, as well as a reaction control system (RCS) and a reaction wheel (RW) to control the position and attitude of the spacecraft.

Landing support is provided by a light detection and ranging (LIDAR) laser altimeter to measure the distance to the asteroid, an optical navigation camera-W1 (ONC-W1) to grasp the spacecraft's position relative to the asteroid, target markers (TMs) to provide landmarks on the asteroid, a flash (FLA) to make the TMs reflect light, and a laser range finder (LRF) to measure four points on the asteroid's surface to find the gradient and distance with respect to the local surface on the asteroid.

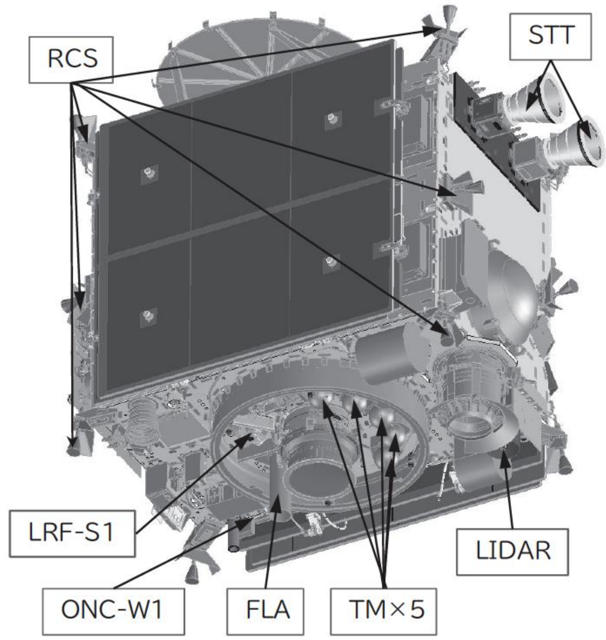

Fig.1 Schematic picture of GNC system of Hayabusa2

3. Touch-Down to Ryugu with GNC system

Fig2 shows the schematic picture of TD sequence. TD sequence is divided into two parts, *Approach phase* and *Final descent phase*.

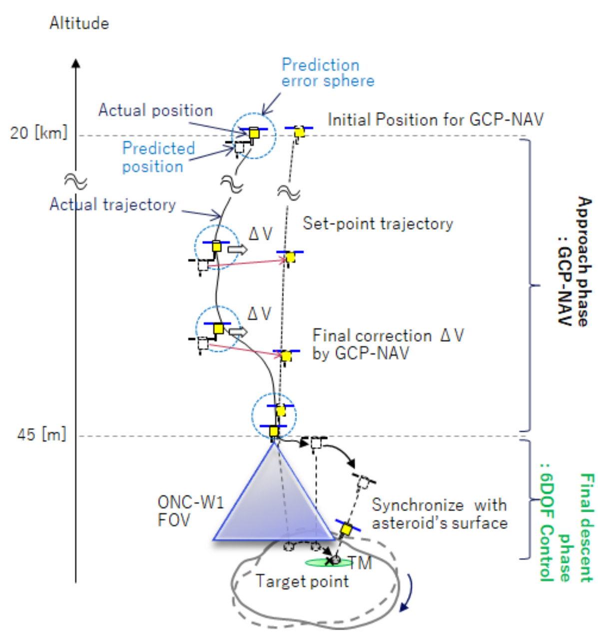

Fig.2 Schematic picture of TD sequence

3.1 Approach Phase

At the beginning of the approach phase, the spacecraft executes a descent maneuver to start descending towards the asteroid from Home Position (hereafter HP: 20km).

In order to acquire the TM on Ryugu, the spacecraft shall reach above the TM (45m: TM visible altitude) at the target time when the asteroid rotation brings the TM onto the approach path.

We have adopted "GCP-NAV (Ground Control Point Navigation)", which is heritage from Hayabusa mission, as navigation and control method. In GCP-NAV, the ground operators manually overlay the asteroid's shape and GCPs (Ground Control Point, that is, characteristic geography) on estimated asteroid shape and GCPs by using the spacecraft attitude and then estimate the spacecraft's position at the time when the image has taken [3][4]. The ground operators propagate the spacecraft's position until next control timing considering large propagation delay (20min for one-way) and then send orbit control commands back to the spacecraft.

3.2 Final Descent Phase

As soon as the TM was visually confirmed at the altitude of 45 m, the spacecraft switched to autonomous navigation, guidance and control while referencing the TM. Fig. 3 shows the schematic picture of final descent phase. Thanks to the asteroid rotation, TM is visible at the edge of ONC-W1 field of view. After acquiring and tracking the TM, the spacecraft control onto TM. Then the spacecraft descent by RCS to 25m. The altitude sensor is switched from LIDAR to LRF around 25m. After that, the spacecraft is controlled to 8.5m (TD start altitude) and then the spacecraft is controlled to TD start point and attitude. Finally, descent maneuver is executed to execute TD to Ryugu.

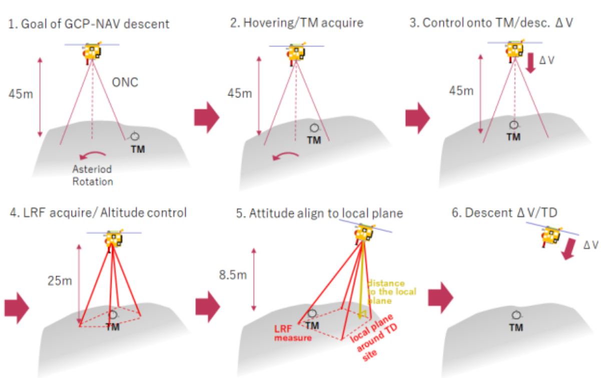

Fig.3 Schematic picture of final descent phase

3.3 Touch-Down Technology

3.3.1 Optical Navigation

The TD target point was specified in a coordinate system, specifically the navigation target (NT) coordinate system, with the target TM on the asteroid set as the origin of the coordinate system using close-up images obtained in the rehearsal for the landing. To estimate the position of the spacecraft in the NT coordinate system, information on the TM's orientation and altitude when viewed from the spacecraft in the NT coordinate system was required.

Fig.4 shows the overview of the autonomous navigation. Designed to recognize the TM, the image processing processor (ONC-E) gave an imaging command and flashing command to the ONC-W1 and FLA respectively and extracted the TM by processing images. Using the CCD address in the ONC-W1's angle of view and the attitude estimation during imaging, the attitude and orbit control processor (AOCP) calculated the TM's orientation in the NT coordinate system when viewed from the spacecraft. The AOCP also calculated the altitude obtained from the LIDAR or LRF.

The AOCP estimated the position and velocity of spacecraft in the NT coordinate system by using the TM's orientation and altitude using a Kalman filter (see Appendix A).

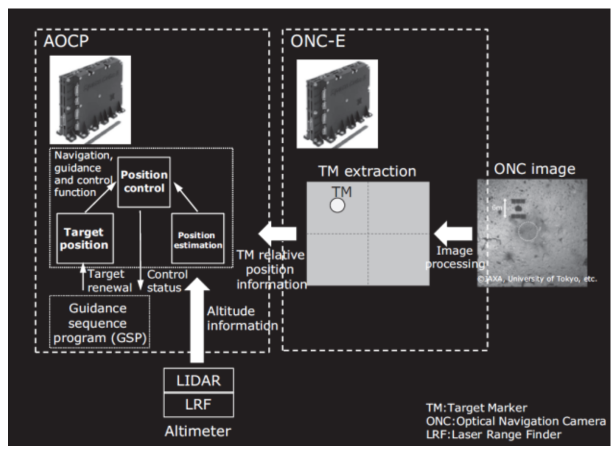

Fig.4 Overview of the autonomous GNC system

3.3.2 Navigation and Control by GSP

Before Hayabasa2 arrived at Ryugu, the asteroid's geographical features and environmental conditions were unclear, making it necessary that the spacecraft be able to modify the TD sequence after arrival. To facilitate this, we added a programmable guidance sequence program (GSP) function to the attitude control flight software (ACFS), which is incorporated in the AOCP. The GSP function is composed of two tables: a conditional branch table (CBT) that monitors the status of the spacecraft and defines a branch accordingly and a command memory table (CMT) that executes a command according to the branch (Fig. 5). GSP has realized autonomous guidance and control for final descent phase described in *3.2*.

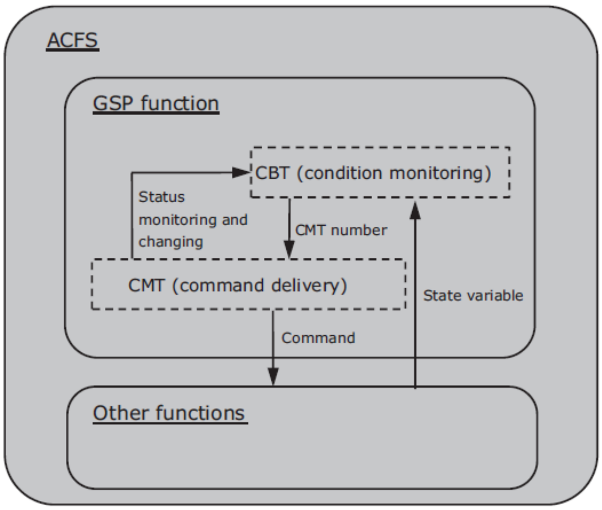

Fig.5 Overview of GSP function

3.3.3 Simulation result

Fig.6 shows the simulation result of TD with our software simulator. The blue and orange plots are sensor data from LIDAR and LRF. The yellow and light blue lines are estimation of altitude by on-board navigation and true altitude of the spacecraft.

The spacecraft descents by GCP-NAV and reaches around 45m. At 45m, the CBT monitors TM tracking state and once the TM tracking state change from “NOT TRACK” to “TRACK”, the CBT executes state transition and the CMT issues commands for controlling onto TM and commands for descending to 25m. Around 25m, CBT monitors LIDAR and LRF altitude and the difference of altitude both is less than 3m, the CBT executes state transition and the CMT issues commands for changing the altitude sensor from LIDAR to LRF. After conversion of position control at 25m, the spacecraft descents to 8.5m.

Fig.7 also shows the simulation result of CCD address X and Y of ONC-W1 (the red and blue lines). This graph indicates the TM is visible the edge of field of view of ONC-W1 at first. After tracking TM, the spacecraft moves onto TM at 45m (the red and blue lines are around 256 that is center of view). At 8.5 m, the spacecraft controls to above TD position (the red and blue lines are separated from center of view). After controlling the position and attitude of TD, we can see the descent delta-V is executed and after detecting the TD, the ascent delta-V is executed. We can see the result of simulation is very similar to the flight data that explained the following section.

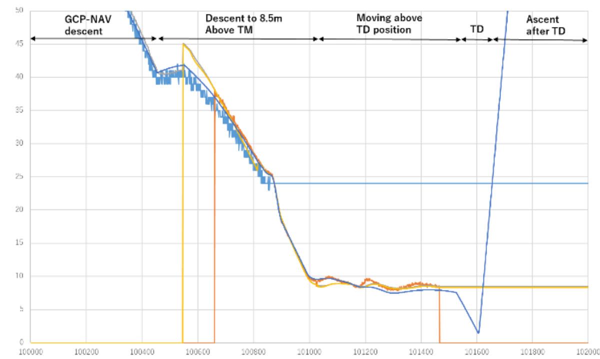

Fig.6 Simulation result of TD
(Time history of altitude)

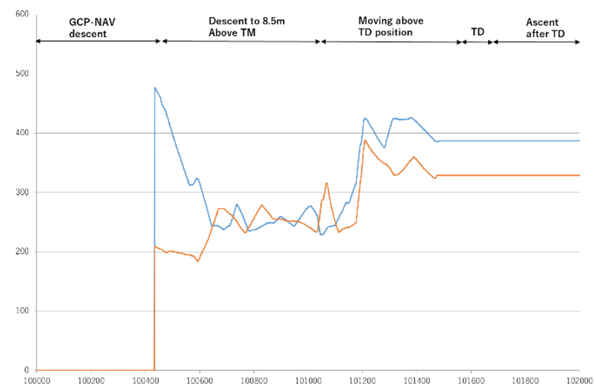

Fig.7 Simulation result of TD
(Time history of ONC CCD address)

4. Flight Results

4.1 First Touch-Down

On February 22, 2019, Hayabusa2 departed its home position at 20 km above the asteroid and descended towards the surface, arriving on schedule at its pre-landing position, 45 m above the TM at 22:07 (UTC).

Fig. 8 shows the history of the CCD addresses of the TM measured in X and Y coordinates as viewed from the ONC-W1 (yellow cross shows address X and blue cross shows address Y) and of the altitudes obtained from the LIDAR (blue dots) and the LRF (orange dots). To begin with, a TM was captured at the edge of the ONC-W1’s angle of view at an altitude of 45 m. The spacecraft used autonomous control to move to a position directly above the TM, thereby moving the TM to the center of the angle of view. While maintaining its position directly above the TM, the spacecraft descended to an altitude of 8.5 m as showed in Fig.9. At 8.5 m, the spacecraft moved to a position directly over the landing site as determined by the relative positions of the previously dropped TM. After changing the attitude to the touchdown attitude, we initiated descent control and detected TD at 22:29 (UTC).

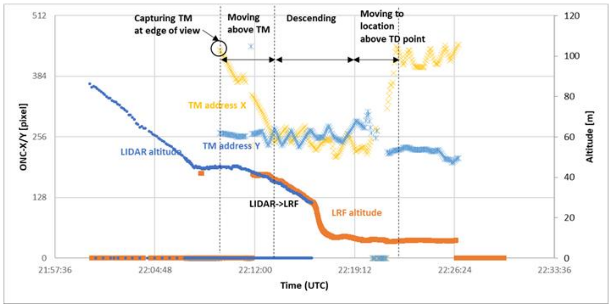

Fig.8 Flight data of first TD operation

Fig.9 Hayabusa2 hovering at 8.5m from Ryugu surface

4.2 Sequence Changes by Guidance Sequence Program

After first TD, there were other surprise as well. Dust blown up from the surface during the first landing caused the performance of the ONC-W1, LIDAR, and LRF to deteriorate, forcing us to adjust the TM visibility altitude (45m to 35m) and the LIDAR/LRF switching altitude (28m to 17m). We modified the CBT and CMT for both functions, which ensured that we were able to execute the second landing without any problems. As a result, a large amount of samples has found in the capsule and provided significant keys to the origin of the solar system and the origin of life on Earth.

Fig.8 Optical microscope image of samples in capsule

5. Conclusions

We have presented Hayabusa2 onboard guidance navigation control system, which contributed to two times high precision TD to Ryugu. This system including guidance sequence program (GSP), which flexibly responds to multiple sequence changes is applicable many other space activities including the assessment and removal of space debris, refueling in space, and so on.

Appendix A (Onboard Optical Navigation)

(a) Basic equations

In order to estimate the positon and velocity of spacecraft relative to Ryugu or TM, we use the Kalman filter. Basic equations of Kalman Filter consist of time update and observation update. For time update,

$$\bar{x}_k = A_k \hat{x}_k + B_k u_k \quad (1)$$
$$\bar{P}_k = A_k P_k A_k^T + Q_k \quad (2)$$

,where A_k is the state transition model which is applied to the previous state variable $\hat{x}_k$, B_k is the control input model which is applied to the control vector u_k, P_k is covariance matrix and Q_k is the covariance of process noise. For observation update,

$$K_k = \bar{P}_k H_k^T (H_k \bar{P}_k H_k^T + R_k)^{-1} \quad (3)$$
$$\hat{x}_k = \bar{x}_k + K_k(z_k - H_k \bar{x}_k) \quad (4)$$
$$P_k = (I - K_k H_k)\bar{P}_k \quad (5)$$

,where K_k is Kalman gain, H_k is observation model, which maps the true state space into the observed space, R_k is the covariance of observation noise.

(b) State Equation

In Final descent phase of Hayabusa2, state variable is defined the position and velocity in the Navigation Target coordinate system.

$$x_k \equiv (\ \vec{r}_{SC/NT}, \vec{v}_{SC/NT}\ ) \quad (6)$$

State equation [eq.(1) above] for Hayabusa2 is

$$\dot{\vec{v}}_{SC/NT} = g_{/NT} + \Delta V_{/NT}/\Delta t \quad (7)$$
$$\dot{\vec{r}}_{SC/NT} = \vec{v}_{SC/NT} \quad (8)$$

,where $g_{/NT}$ is gravity in NT coordinate system and $\Delta V_{/NT}/\Delta t$ is control input by RCS.

(c) Observation Equation

Observation model H_k is determined by relationship between the state variable and the observation variable. Fig9 shows the relationship between the position in NT coordinate system ($\vec{r}_{SC/NT}$) and the altitude observed by LRF (L). From geometric relationship shown in Fig.9 we can obtain the following equation.

$$L = |\vec{r}_{LO/NT} - \vec{r}_{SC/NT}| \quad (9)$$

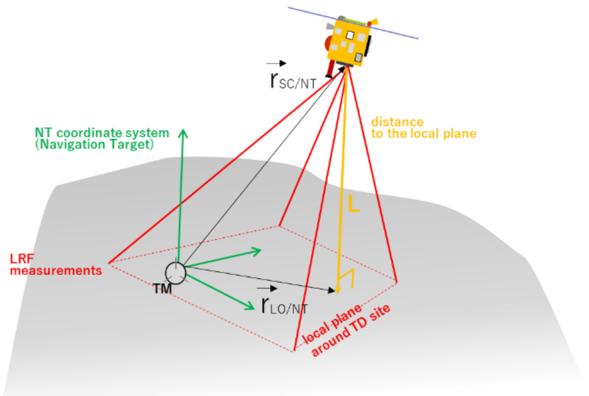

Fig.9 Spacecraft in NT coordinate system

Same as above, TM's orientation ($\vec{n}_{/SC}$) is written in the following equation.

$$\vec{n}_{/SC} = (\vec{r}_{CO/NT} - \vec{r}_{SC/NT}) / |\vec{r}_{CO/NT} - \vec{r}_{SC/NT}| \quad (10)$$

Using the above as the basic observation formula, we derive the observation equation whose observation value is L, nX/nZ(≡pX) , and nY/nZ(≡pY). If we define $\vec{Z}^* \equiv (L, pX, pY)^T$, we can obtain the following equation.

$$\vec{Z}^* = \vec{h}(\vec{X}) = \begin{pmatrix} |\vec{r}_{LO/NT} - \vec{r}_{SC/NT}| \\ (\vec{r}_{CO/NT} - \vec{r}_{SC/NT})_X / (\vec{r}_{CO/NT} - \vec{r}_{SC/NT})_Z \\ (\vec{r}_{CO/NT} - \vec{r}_{SC/NT})_Y / (\vec{r}_{CO/NT} - \vec{r}_{SC/NT})_Z \end{pmatrix} \quad (11)$$

If we write $\vec{X} = \overrightarrow{X_0} + \delta\vec{X}$, we can obtain the linearized observation equation. $\boldsymbol{H}(\overrightarrow{X_0}) \equiv (\boldsymbol{H_{LDR}} \quad \boldsymbol{H_{ONC}})$

$$\vec{Z} = \boldsymbol{H}(\overrightarrow{X_0}) \cdot \vec{X} \quad (12)$$

$$\boldsymbol{H_{LDR}} = \left(-(\boldsymbol{x_{LO}} - \boldsymbol{x})/|\vec{r}^*| \quad -(\boldsymbol{y_{LO}} - \boldsymbol{y})/|\vec{r}^*| \quad -(\boldsymbol{z_{LO}} - \boldsymbol{z})/|\vec{r}^*| \right) \quad (13)$$

$$|\vec{r}^*| \equiv |\vec{r}_{LO/NT} - \vec{r}_{SC/NT}|$$

$$\boldsymbol{H_{ONC}} = \begin{pmatrix} -1/(\boldsymbol{z_{CO}} - \boldsymbol{z}) & \boldsymbol{0} & (\boldsymbol{x_{CO}} - \boldsymbol{x})/(\boldsymbol{z_{CO}} - \boldsymbol{z})^2 \\ \boldsymbol{0} & -1/(\boldsymbol{z_{CO}} - \boldsymbol{z}) & (\boldsymbol{y_{CO}} - \boldsymbol{y})/(\boldsymbol{z_{CO}} - \boldsymbol{z})^2 \end{pmatrix} \quad (14)$$

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