Cooperative Radio Navigation for Robotic Exploration: Evaluation of a Space-Analogue Mission

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***Abstract*—Autonomous robotic systems will play an important role in future planetary exploration missions. To allow autonomous operation of robots, reliable navigation is vital. Such a navigation solution is provided by cooperative radio navigation, where radio signals are exchanged among the robots. Based on the signal round-trip time (RTT) and direction-of-arrival (DoA), the robots' positions and orientations are estimated. Cooperative navigation has been well studied theoretically, but experiments mainly focused on indoor scenarios and other applications. For the first time, we have demonstrated cooperative radio navigation within a space-analogue exploration mission with two robotic rovers. The mission took place on the volcano Mt Etna, Sicily, Italy. During the first part of the mission, simultaneous localization and calibration (SLAC) is performed to improve the accuracy of RTT and DoA estimates by reducing the bias. Then, the rovers travel to a distant area of interest. Ultimately, one rover travels so far that it is connected to the network only via another rover. We find that even in this challenging single-link scenario, robust cooperative navigation is achieved. When the rovers are not further than 60 m away from the lander, their position root-mean-square errors (RMSEs) are 0.3 m to 0.9 m. Even for the most challenging mission phase, when the rovers are 100 m to 160 m away from the lander with single-link localization, the position RMSEs are 1.7 m to 2.6 m. The orientation RMSEs of the rovers lie between 2.4° to 6.1°. Thus, with this space-analogue mission, we show that cooperative radio navigation for planetary exploration is robust and accurate.**

***Index Terms*—Cooperative localization, ranging, direction-of-arrival, software-defined radio, simultaneous localization and calibration, SLAC**

I. Introduction

Autonomous robotic systems will play a crucial role in future planetary exploration missions [1]. Robotic multi-agent systems can be composed of heterogeneous robots and thus combine the potential of e.g. ground-based and airborne robots [2]. To enable autonomous robotic exploration, reliable navigation is essential. Both, the positions and orientations of the robots must be estimated and tracked over time. Positions and orientations are necessary to control the robots, but also to know e.g. where scientific measurements and camera images were taken.

Thus, cooperative radio navigation has been proposed for planetary exploration [3]. By cooperative navigation, radio signals are exchanged among all agents in the network. Distance and direction information obtained from the signal round-trip time (RTT) and direction-of-arrival (DoA) allow the estimation of positions and orientations of the agents. In addition to planetary exploration, cooperative navigation is also considered for e.g. cellular networks [4] and sensor networks [5]. Cooperative navigation has been investigated theoretically in [6], [7] and an overview of cooperative navigation algorithms can be found in [8]. When distance and direction information is available, so called single-anchor or single-link localization can be performed [9].

To achieve accurate cooperative navigation also in challenging scenarios, calibration is crucial. To obtain a meaningful distance estimate from the signal RTT, group delays in the transceivers and antennas must be compensated. For accurate DoA estimation, the antenna response of the multiport antenna, i.e. its amplitude and phase patterns, must be determined. However, these calibration parameters could change over time, thus calibrating the system only once does not guarantee ongoing good performance. Transceiver group delays are subject to temperature changes and antenna responses and group delays are influenced by changes in the surroundings of the antenna. As an example, consider a small robot with a manipulator arm, which is capable of grabbing and carrying payload boxes [10]. Therefore, cooperative simultaneous localization and calibration (SLAC) has been introduced to estimate calibration parameters during operation [11], [12],

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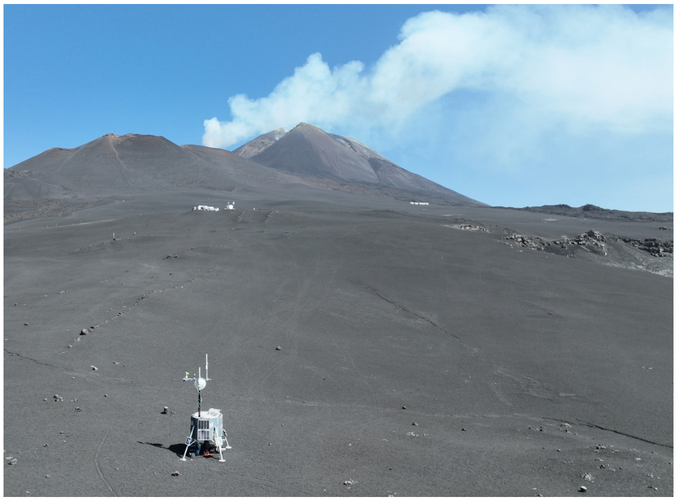

Fig. 1. Picture of the lander and the demo mission area, which is behind and to the right side of the lander.

[13]. Cooperative navigation has been evaluated experimentally in indoor environments [14], [15] and tests in outdoor environments have been conducted [16].

However, thorough evaluation of cooperative radio navigation for an entire space-analogue exploration mission with robots has not been done yet. Especially single-link localization lacks experimental validation.

In this paper, we analyze cooperative radio navigation during a space-analogue demonstration mission, see Fig. 1. The mission features two robotic rovers and consists of four mission phases, which cover different aspects of cooperative radio navigation. First, the rovers drive around the closer vicinity of the lander and SLAC is performed to calibrate the system. Then the rovers travel to a distant area of interest. Ultimately, one rover is only connected to the network via the other rover, which yields a challenging single-link localization scenario. Finally, the two rovers safely return to the lander. The demonstration mission has been performed in a space-analogue environment on the volcano Mt Etna, Sicily, Italy.

The paper is organized as follows. First, in Section II, we introduce our cooperative radio navigation system. Next, in Section III, we introduce the mission, the involved systems and different mission phases. In Section IV, we provide an in-depth evaluation of the space-analogue mission regarding important aspects and performance measures of cooperative radio navigation. Section V concludes the paper.

II. Cooperative Radio Communication and Navigation

A joint radio communication and navigation system for a planetary exploration mission should support both, high update rates and high data rates [17]. To fulfill that, our developed system is based on orthogonal frequency-division multiplexing (OFDM), which is spectrally efficient and used in many state-of-the-art communications systems, e.g. IEEE 802.11 Wi-Fi and 4G and 5G cellular networks. To make the system flexible and avoid a central scheduling entity, the channel is accessed by self-organized time-division multiple access (TDMA).

TABLE I
Joint communication and navigation system parameters.

Parameter	Value
Carrier frequency	1.68 GHz
Sampling rate	31.25 MHz
Occupied bandwidth	≈ 28.2 MHz
TDMA schedule	100 ms
Transmit power	5 dBm

For node identification and ranging, each node is assigned a unique preamble. We have chosen Zadoff-Chu sequences [18] with low cross-correlation properties. Furthermore, allocation of every second subcarrier enables efficient OFDM frame synchronization by differential correlation [19]. The time-of-arrivals (ToAs) of the received signals are estimated using the known preambles. From the ToAs, the signal RTT is calculated, which translates to a distance estimate. The impact of the clock drift is compensated by clock tracking, see [17] for details. Equipping nodes with a multiport antenna, e.g. an antenna array or an multi-mode antenna (MMA) [20], [21], allows joint ToA and DoA estimation. Direction information is beneficial for orientation estimation and enables single-link localization, see Section III-C.

The cooperative radio communication and navigation system is implemented as software-defined radio (SDR) based on GnuRadio and Ettus Research Universal Software Radio Peripherals (USRPs). Details on the implementation can be found in [16]. Important system parameters are summarized in Table I. For accurate navigation, a thorough calibration of the system is vital. For RTT ranging, group delays in the transceivers must be compensated to avoid biased ranging. Firstly, the transmitted signals are observed by leakage through a radio frequency (RF) switch. Secondly, remaining internal transceiver group delays are calibrated before the mission in the lab. Thirdly, any remaining ranging biases, e.g. due to the antenna or the rover structure in the near-field of the antenna, are calibrated during mission execution by SLAC [11], [13]. For DoA estimation, the antenna response of the multiport antenna must be known accurately. Any deviation of the true antenna response from the assumed antenna response will result in biased DoA estimates and degrade performance.

The positions and orientations of the nodes are estimated by an algorithm called cooperative SLAC [11], [13]. Simultaneously to position and orientation estimation, the algorithm estimates antenna responses of multiport antennas, direction-dependent ranging biases of rovers, and constant ranging biases of static nodes. The core of cooperative SLAC is a Bayesian filter. We refrain from repeating the algorithmic details here and instead refer the reader to [11], [13]. In [11], the cooperative SLAC algorithm is described in detail and its effectiveness is shown by simulation. The extension to direction-dependent ranging biases is described in [13].

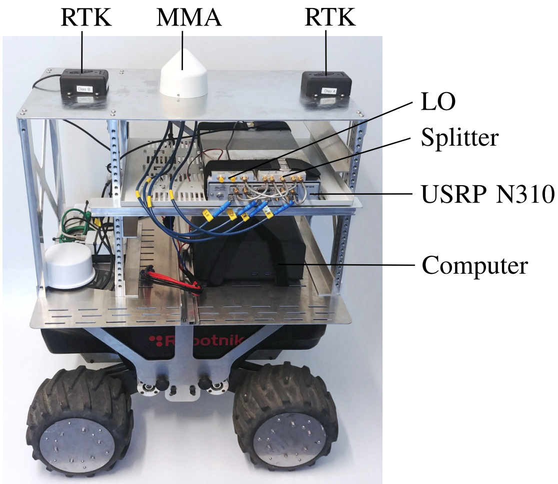

Fig. 2. Rover Dias with installed MMA, see [23], multichannel SDR USRP N310 and two antenna RTK system for position and orientation ground truth.

Fig. 3. Anchor box with antennas and a docking adapter that allows manipulation by a robot.

III. Space-Analogue Exploration Mission

A. Overview

The space-analogue exploration mission to demonstrate cooperative radio navigation has been performed in the frame of the Helmholtz future project ARCHES [22]. The goal of ARCHES was to demonstrate technologies for future space exploration missions. Specifically, it was shown how a mission with a significantly higher level of autonomy compared to current missions could be performed, where heterogeneous teams of robots cooperate to solve complex tasks [2]. The project final demonstration took place as a space-analogue mission on the volcano Mt Etna on Sicily, Italy, in June and July 2022.

Our space-analogue mission, which we refer to as mission in the following, is split into four phases, which are described in Section III-C. A picture of the lander and the mission area can be seen in Fig. 1. The picture also gives an impression of the terrain. Behind the lander follows a dip, before the hill rises.

B. Systems and Entities

The rover Dias shown in Fig. 2 is equipped with a four-port MMA [23], which enables DoA estimation [11]. The antenna response of the MMA has been measured in a near-field measurement chamber beforehand. Impacts of the rover structure are taken into account by calibration during the mission by SLAC. The MMA is connected to a four-channel USRP N310, which is operated with an external local oscillator (LO) to provide four phase-coherent channels. Furthermore, the rover is a equipped with a computer for signal processing and a commercial two antenna RTK system for position and orientation ground-truth. The second rover, Vespucci, is equipped with an omnidirectional antenna and a single-channel USRP B200mini. Thus, Vespucci is capable of ranging, while Dias is capable of ranging and DoA estimation. Both are equipped with a gyroscope, which is used to aid the SLAC algorithm together with the command linear velocity of the rover [12]. Direction-dependent ranging biases, e.g. caused by the impact of the rover structures in the near-field of the antennas, are estimated during the mission by SLAC.

Three anchor boxes called A1, A2 and A3 are located in 17 m to 40 m distance to the lander. They are designed in a compact fashion, see Fig. 3, and a docking adapter allows manipulation by a robot [2]. For this mission, they are pre-deployed and their positions are assumed to be known. The anchor boxes are equipped with USRP B200minis and omnidirectional antennas. Furthermore, two payload boxes with unknown positions, but otherwise similar setup, are also part of the mission. The lander shown in Fig. 1 is also equipped with a radio node. A USRP B210 is installed inside the lander and a directive antenna, facing the mission area, is mounted on the extendable pole. Ranging biases of the anchor nodes and the lander node are estimated during the mission by SLAC.

C. Mission Phases

Fig. 4 shows an aerial image of the mission area on the volcano Mt Etna. The lander depicts the origin of the local Cartesian coordinate system. Furthermore, the positions of the three anchor boxes and the two payload boxes are shown, as well as the trajectories that the two rovers Dias and Vespucci traveled during the whole mission. The figure also gives an impression of the size of the experiment area. At the farthest point, Vespucci was more than 150 m away from the lander.

The space-analogue exploration mission is structured in four distinct phases, which are outlined in Table II. In phase I, the rovers move around the closer vicinity of the lander, in-between the anchor and payload boxes. Proper operation of the cooperative radio navigation system is verified. Furthermore, the antenna response of the MMA on Dias, the direction-dependent ranging biases for Dias and Vespucci and the constant ranging biases of the anchors, payload boxes and the lander are estimated by SLAC. Thereby, localization accuracy is improved and the system is prepared for more challenging cooperative localization scenarios. In phase II, the rovers move

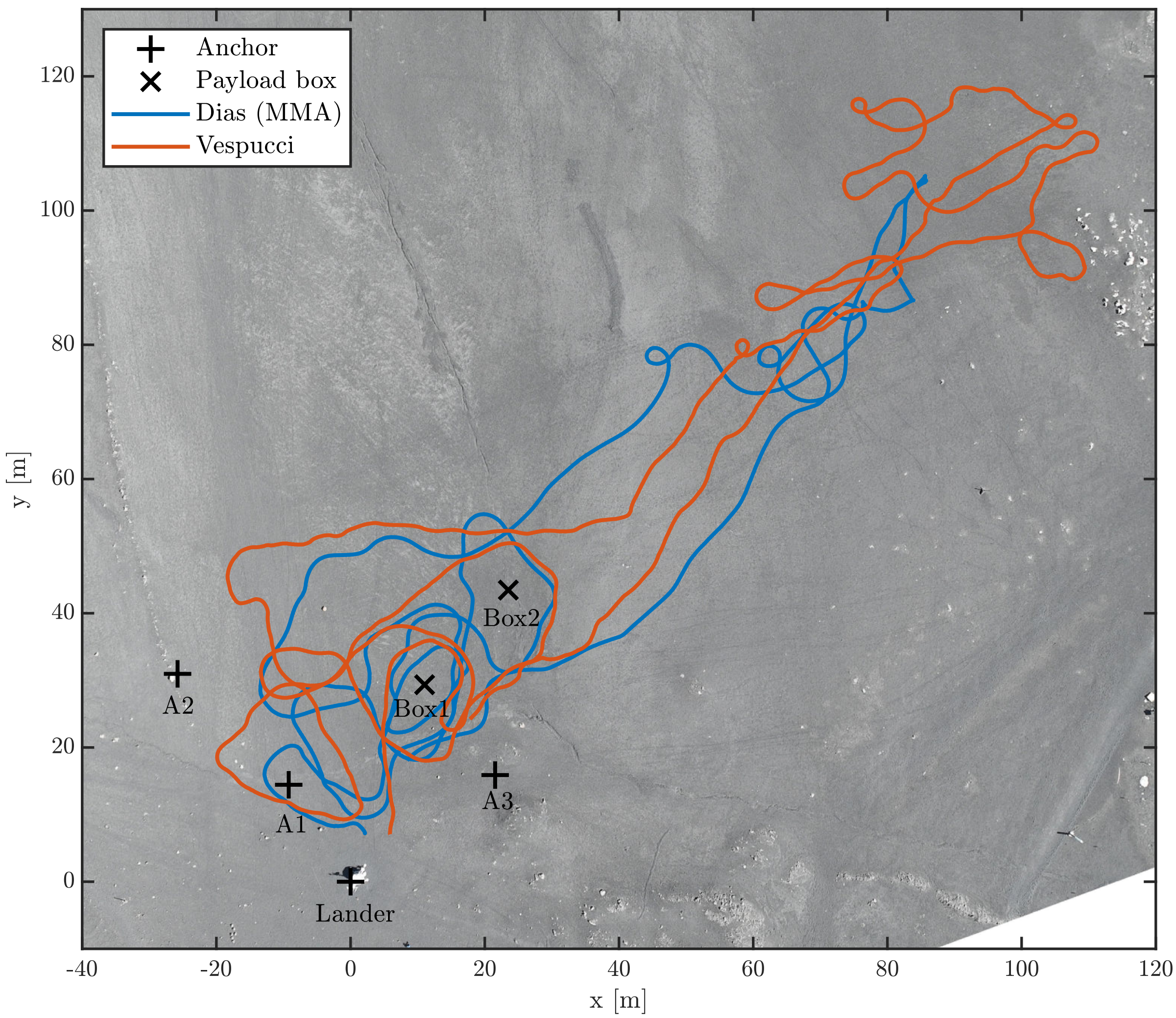

Fig. 4. Aerial image of the demo mission area on the volcano Mt Etna with lander, anchor and payload box positions and rover trajectories.

TABLE II
SPACE-ANALOGUE EXPLORATION MISSION PHASES.

Phase	Description	Objectives	Outcome
I	SLAC	Commissioning, calibration by SLAC, payload-box localization	Calibrated antenna response, (direction-dependent) ranging biases
II	Travel	Move to area of interest	Rovers reach area of interest
III	Single-link localization	Explore area of interest	(E.g. map of area of interest, rock samples, ...)
IV	Return-to-base	Return to the lander	Rovers are ready for next mission (E.g. sample return)

to the distant area of interest, which they explore in phase III. The area of interest is far away from the lander and the anchors, such that Vespucci ultimately loses connections to all nodes except Dias. Dias is capable of both, ranging and DoA estimation, and hence enables single-link localization of Vespucci. An illustration of single-link localization with two rovers is shown in Fig. 5. Finally, when the rovers have finished exploring the area of interest, they return to the lander in phase IV.

IV. Mission Evaluation

A. Overview

We now evaluate the mission, focusing on important aspects of cooperative radio navigation. First, we look at maps of the four mission phases in Fig. 6 in order to better understand their individual characteristics and challenges. The ground-truth trajectories of the rovers are plotted in black and their estimated trajectories are overlayed in the respective color. The rover positions and orientations at the end of each phase are indicated by circles and lines. In phase I, the rovers drive around in the area close to the lander, in between the anchors

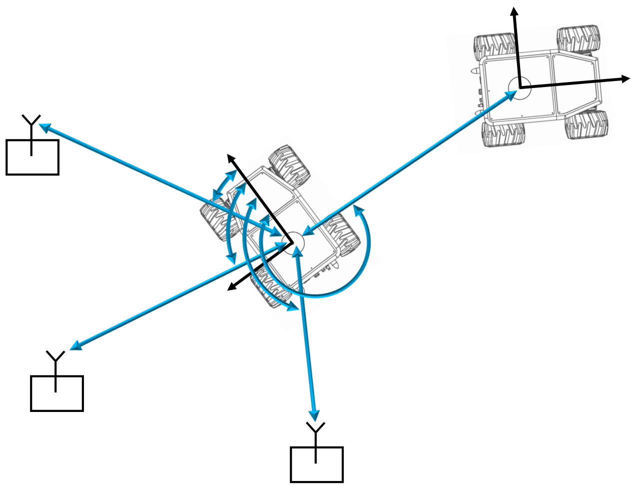

Fig. 5. Illustration of single-link localization with three anchors, one rover capable of DoA estimation and ranging and one rover capable of ranging.

and payload boxes. The rover trajectories are estimated with high accuracy, the trajectories almost perfectly overlay the ground-truth. In this phase, the payload box positions and the calibration parameters are estimated by SLAC. Next, in phase II, the two rovers travel to a distant area of interest, which is more than 100 m away from the lander. As the rovers drive far away, the positioning accuracy decreases. The reason is mainly the very challenging geometry for localization. All anchors are located far away and in a similar direction from the rovers. Phase III constitutes the most challenging mission phase for navigation. For large parts of this phase, Vespucci is connected to the network only through a single link via Dias. This single-link localization is only possible since Dias is capable of estimating the DoA of incoming radio signals in addition to ranging, thus providing valuable direction information in addition to distance information. Since Dias is also located far from the anchors, its position and orientation estimates have medium accuracy, see more details in Section IV-D. Due to single-link localization, Dias' position and orientation errors propagate to Vespucci. Furthermore, single-link localization by itself is very challenging. For these reasons, the trajectory of Vespucci shows the highest errors in this phase. Nevertheless, cooperative radio navigation is proven to be robust, even in these challenging circumstances. Finally, in phase IV the two rovers return to the lander area. Localization performance is similar to phase II reversed. With the rovers approaching the anchors, the accuracy increases.

B. Rover RF links and SNR

In Fig. 7, the number of radio links of Dias and Vespucci averaged over one second, corresponding to ten TDMA cycles, is shown. The plot reveals that in phase I, Dias and Vespucci have good connectivity with four to seven links. In phase II, when the rovers are driving away from the lander area, the connectivity of Vespucci is already impaired for short periods of time. For both phases, the connectivity of Dias turns out to be superior to Vespucci, which shows the advantage of the four-port MMA installed on Dias. For most of phase III, we see that Vespucci has only one link, which is the link to Dias. Furthermore, we see that in the first part of phase III, Dias partially suffers from poor network connectivity. After it is re-positioned, it obtains three to four stable links. In phase IV, the rovers are returning to the lander area and connectivity improves again. Since the antennas on the rovers and the payload boxes are relatively low above ground, it should be noted that shadowing due to uneven terrain is likely.

Fig. 8 shows the estimated SNR from OFDM frame synchronization [19] for the signals received from its neighboring nodes. We observe that the SNR is varying quickly. As the rovers are moving, this is caused by fast fading due to multipath propagation, especially the ground reflection. Below approx. 3 dB no ranging is possible, since the data packet containing the transmit timestamp cannot be decoded. It also strikes attention that signals received from Dias usually have higher SNR compared to the other nodes. The reason is probably twofold. First, the two rovers are often driving relatively close to each other. Second, the MMA installed on Dias is coherently fed on two ports to provide an approximately omnidirectional transmit pattern, which increases transmit power.

C. Rover Ranging and DoA Estimation

Fig. 9 shows the ranging root-mean-square error (RMSE) calculated over all links of the rover Dias for standard RTT ranging and two versions of SLAC with ranging bias compensation. SLAC v1 refers to the original cooperative SLAC algorithm introduced in [11], which estimates constant ranging biases for all agents and anchors. SLAC v2 has been extended to direction-dependent ranging biases for Dias and Vespucci in order to compensate group delay variations caused by the antenna and rover structure close to the antenna, see [13]. The ranging RMSE is calculated over all active links in the respective TDMA cycle. Initially, we see a high ranging RMSE up to more than 2.5 m. The ranging biases have not yet been estimated, and Dias is close to the lander, which could cause multipath propagation due to signal reflections and scattering. Then, the ranging RMSE of Dias quickly decreases and stays mostly below 0.5 m. Both versions of SLAC exhibit considerably lower ranging RMSE compared to standard RTT ranging, which shows the effectiveness of ranging bias compensation by SLAC. Furthermore, SLAC v2 with direction-dependent ranging bias compensation outperforms SLAC v1, which only considers constant ranging biases. When Dias is further away from static nodes in phases II and III, short periods with larger ranging RMSE are apparent. Especially for those periods, SLAC v2 shows a considerable improvement. Calculated over phases II-IV, the ranging RMSE of Dias with RTT is 0.61 m, with SLAC v1 it is 0.34 m and with SLAC v2 it is 0.28 m. Due to the very challenging localization geometries in phases II-IV, where the rovers are far away from the anchors, and especially for the single-link localization in phase III, a low ranging RMSE is paramount to ensure localization with sufficient

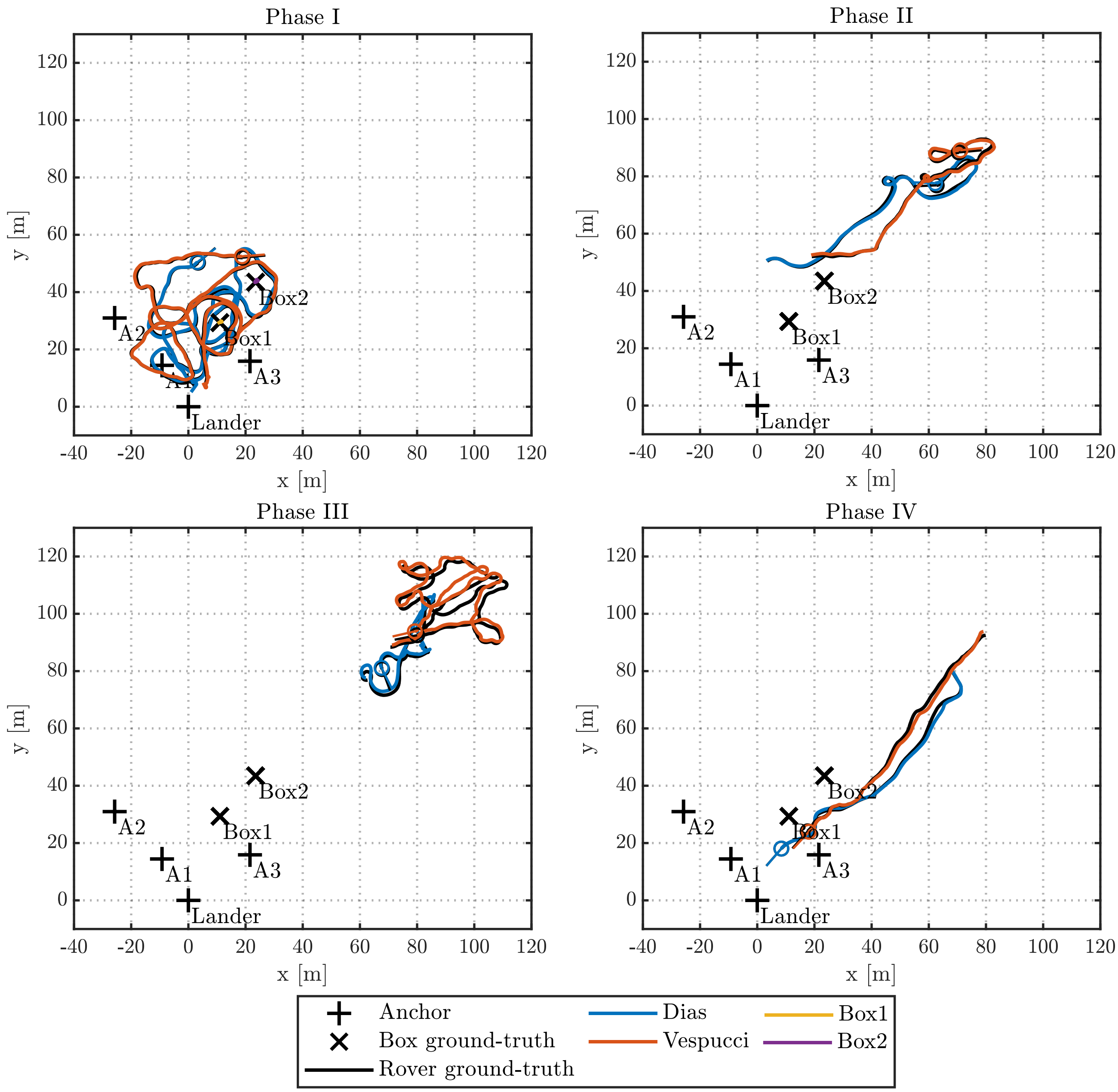

Fig. 6. Maps for all four mission phases with anchor and payload box ground-truth positions as well as estimated rover trajectories and box positions. The box positions are only estimated in phase I. The rover positions and orientations at the end of each phase are indicated by circles and lines.

accuracy. The localization performance is analyzed in detail in the next Section IV-D.

We proceed to analyze the DoA estimation RMSE of the four-port MMA installed on the rover Dias. The DoA estimation RMSE shown in Fig. 10 is calculated over all received signals in the respective TDMA slot. We compare DoA estimation using the antenna response of the antenna alone measured in near-field measurement chamber and using the antenna response estimated by SLAC. At the beginning of phase I, both show similar performance, as SLAC is initialized with the antenna response from the near-field measurement. After about 2 min, SLAC performs better. The original antenna calibration has been improved by SLAC, which leads to better DoA estimation performance. Calculated over phases II-IV, the DoA estimation RMSE of Dias with the antenna response from the near-field measurement is $6.7°$ and with SLAC it is $4.4°$.

D. Rover Position and Orientation Estimation

Now, we analyze the cooperative radio navigation performance in terms of the position and orientation estimation errors. The absolute position errors of the rovers and payload boxes are plotted in Fig. 11 and their position RMSEs for the respective mission phases are shown in Table III. At the

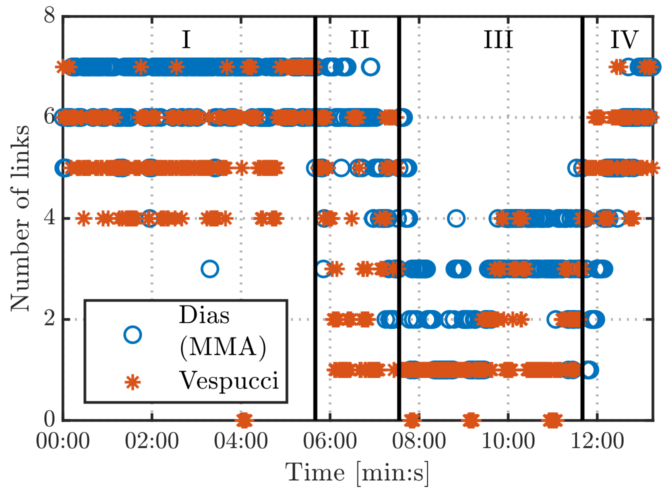

Fig. 7. Number of radio links of the two rovers Dias and Vespucci.

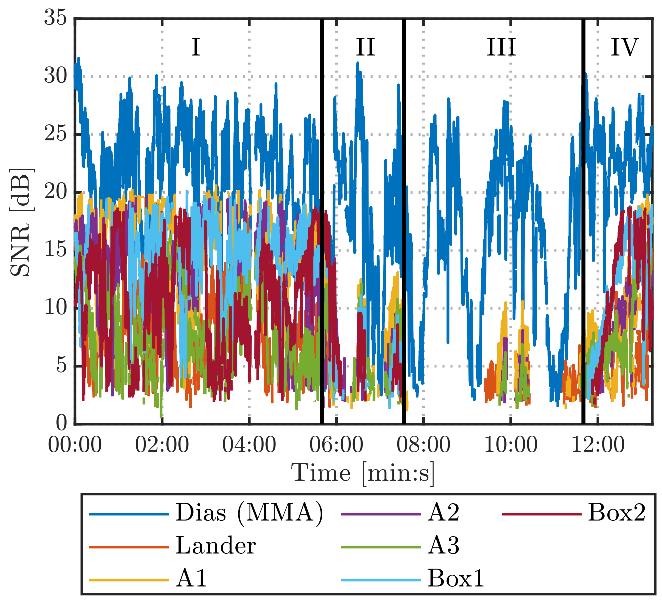

Fig. 8. Estimated SNR of the signals received by Vespucci.

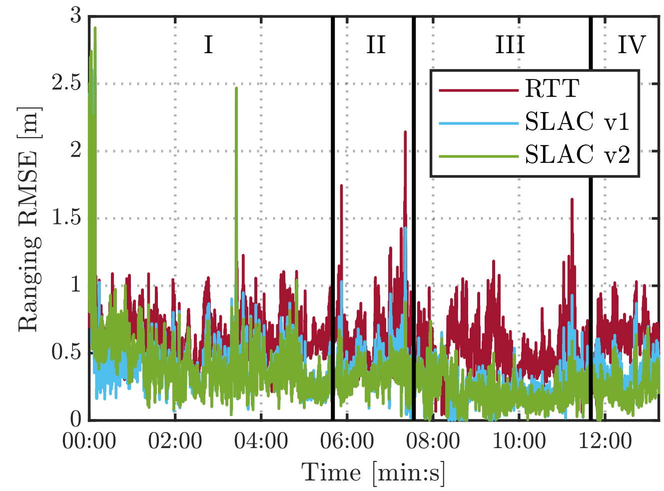

Fig. 9. Ranging RMSE over all links of the rover Dias with MMA for standard RTT ranging, constant ranging bias compensation by SLAC v1 and direction-dependent ranging bias compensation by SLAC v2.

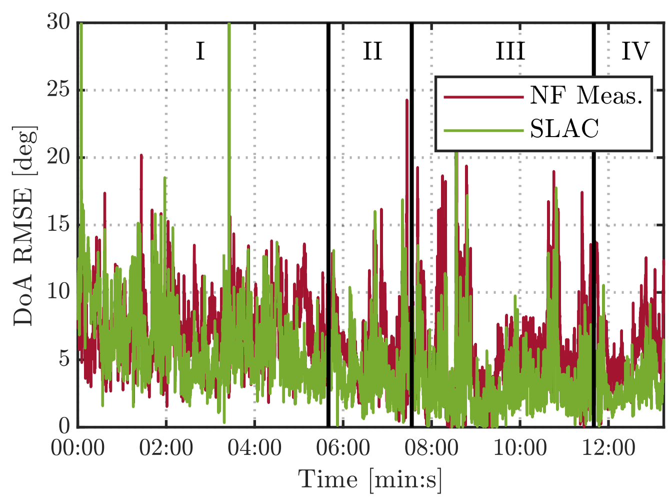

Fig. 10. DoA estimation RMSE over all links of the rover Dias with MMA when DoA estimation is performed using the antenna response obtained by a near-field measurement or by SLAC.

beginning in, phase I, the rovers driver around the anchors and payload boxes, which yields favorable geometries for localization. Hence, the position errors are mostly below 0.5 m. We also note that the payload box positions are estimated more accurately over time. In phase II, the rovers travel further away from anchors and the position errors slightly grow. Phase III entails challenging single-link localization of Vespucci, and Dias partially loses connections to the anchors, see Fig. 7. Thus, the positions errors in phase III are larger. Still, the maximum position error is 4.7 m, which is remarkable since Vespucci is more than 150 m away from the lander, and Dias acting as a relay is also about 120-130 m away.

The absolute orientation estimation errors of the rovers are plotted in Fig. 12 and the orientation RMSEs for the respective mission phases are shown in Table IV. Through the installed MMA, the rover Dias is capable of estimating the DoA of arriving radio signals in addition to ranging. Thus, it can observe its orientation directly. Vespucci, which is equipped with an omnidirectional antenna, is only capable of performing ranging. Vespucci can thus infer its orientation only through motion over time. In phase I, Vespucci partially has lower absolute orientation errors compared to Dias, although their orientation RMSE is similar. In phase I, the antenna response of the MMA installed on Dias is being calibrated by SLAC. Thus, in the beginning, DoA estimation of Dias is less accurate, as discussed in Section IV-C. However, for phases II, III and IV, the orientation RMSE of Dias is clearly lower compared to Vespucci, which shows the benefit of the MMA installed on Dias.

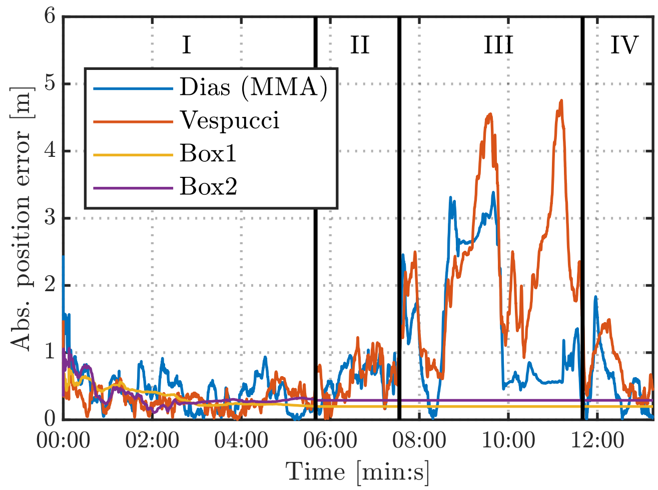

Fig. 11. Absolute position error of the rovers Dias and Vespucci and the two payload boxes.

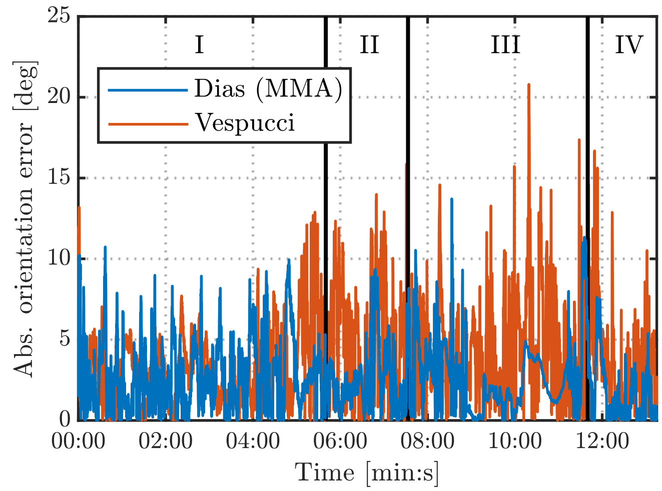

Fig. 12. Absolute orientation error of the rovers Dias with MMA and Vespucci.

TABLE III
POSITION RMSE.

Agent	**Phase I** SLAC	**Phase II** Traveling	**Phase III** Single-link localization	**Phase IV** Return-to-base
Dias (MMA)	0.50 m	0.66 m	1.73 m	0.65 m
Vespucci	0.34 m	0.68 m	2.56 m	0.85 m
Box 1	0.37 m	0.20 m	0.20 m	0.20 m
Box 2	0.39 m	0.29 m	0.29 m	0.29 m

TABLE IV
ORIENTATION RMSE.

Agent	**Phase I** SLAC	**Phase II** Traveling	**Phase III** Single-link localization	**Phase IV** Return-to-base
Dias (MMA)	3.6°	3.1°	3.5°	2.4°
Vespucci	4.0°	6.1°	5.4°	4.7°

V. CONCLUSION

In conclusion, we have successfully demonstrated cooperative radio navigation for two rovers and two payload boxes during an exploration mission in a space-analogue environment. We have shown that calibration during the mission by SLAC lowers the ranging and DoA estimation RMSEs. Accurate ranging and DoA estimation is crucial especially in challenging localization scenarios, e.g. when the rovers are far away from the anchors, since distance and direction estimation errors can then translate to large position and orientation errors. Furthermore, we have successfully demonstrated that rover capable of both, ranging and DoA estimation, allows single-link localization of another rover. Thereby, we could localize a rover more than 150 m away from the lander. Even for this most challenging mission phase, the position RMSEs of the two rovers were 1.7 m and 2.6 m. We consider single-link localization to be a key capability of the rover with multiport antenna. For the other mission phases, where the rovers were closer to the lander, the position RMSEs of the rovers were 0.3 m to 0.9 m. The rover orientation RMSEs were 2.4° to 6.1°. In summary, we have shown that cooperative radio navigation with SLAC is accurate and robust, even in very challenging mission scenarios.

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