

Space Habitat Data Centers – For Future Computing

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Abstract: Data from sensor bearing satellites requires processing aboard terrestrial data centers that use water for cooling at the expense of high data transfer latency. The reliance of terrestrial data centers on water increases their water footprint and limits the availability of water for other applications. Therefore, data centers with low data transfer latency and reduced reliance on earth's water resources are required. This paper proposes space habitat data centers (SHDCs) with low latency data transfer and that use asteroid water to address these challenges. The paper investigates the feasibility of accessing asteroid water and the reduction in computing platform access latency. Results show that the mean asteroid water access period is 319.39 days. The use of SHDCs instead of non-space computing platforms reduces access latency and increases accessible computing resources by (11.9% – 33.6%) and (46.7% – 77%) on average respectively.

Keywords: Space Habitats; Data Centers; Computing Platforms; Asteroids;

1. Introduction

Terrestrial cloud data centres have high powering [1–3] and cooling (using water) [4–5] costs. These have prompted the design of solutions [6–10] that reduce power consumption and water footprint. The water footprint can also be reduced by leveraging on free air cooling [11–12] to a limited extent. The ocean provides free water cooling and can host data centres [13–15] but at the risk of degrading marine bio-diversity.

Siting data centres in space can reduce the water footprint [16–19]. The approach in [16, 18] utilizes small satellites to realize space based data centres. Small satellites used as data centres have reduced uptime when faults occur because they are unmanned. It is also challenging to upgrade the computing payload in small satellites being used as data centres. Outer space also hosts satellites, and spaceships [19–21]. Spaceships such as space habitats can support humans (making it easy to address faults) and host a larger computing payload. This paper proposes a manned space habitat data centre (SHDC) for processing space and non-space application data. The proposed manned SHDC has reduced reliance on earth's water resources for cooling. The contributions are:

First, the paper proposes manned space habitat data centres (SHDCs) for data processing. The paper describes communications between SHDCs, compute resource constrained space assets; and the ground segment. The paper also describes SHDC design and computing entities enabling data processing and communications.

Second, the paper investigates the feasibility of using asteroid water and formulates metrics to investigate the performance benefits of SHDCs. Simulation considers the case where small satellites forward data to SHDCs instead of stratosphere based and terrestrial data centers. The performance metrics are the compute resource access latency and accessible computing resources in the space segment.

The research is described: Section 2 and Section 3 discusses the research background and addressed problem respectively. Section 4 and Section 5 presents the proposed solution and performance model respectively. Section 6 and Section 7 discusses results and concludes the research respectively.

2. Background

The existing work is considered in this aspect that has three parts. The first, second and third part describes the addressed challenge, existing work and solution perspective respectively.

2.1 Challenge Under Consideration

The increasing use of small satellites necessitates increasing data storage and processing capacity. The use of more terrestrial data centres can be used to address this challenge. However, the use of more data centres results in high latency and water footprint. These challenges can be addressed by siting data centers in locations

where they are closer to small satellites and without reliance on earth's water resources. This can be achieved by siting data centres in outer space.

2.2. Existing and Related Work

Space technologies find applications in planetary science and space colonization. Space colonization has received attention from private organizations interested in commercializing space. Yakolev [22] recognizes that the use of space houses (realizable via space habitats) is required for Mars exploration.

Smitherman *et al* [23] recognize the role of space habitats in missions such as asteroid retrieval, access and deep space missions. Space vehicles also have varying capabilities depending on crew size and scientific payload. Space habitat design concepts are derivable international space station and space launch system design perspectives. Concepts from these perspectives ultimately aim to provide a comfortable living space in orbit.

Griffin *et al* [24] identify the knowledge gaps required for space habitat design. The presence of an autonomous communication system aboard space habitats is deemed to be of medium priority. However, the discussion in [24] does not present space habitat network architecture. Instead, the focus of [24] is on the launch and radiation aspects of space vehicle design. The study in [25] describes how habitat modules can be aggregated in realizing the deep space gateway. The large volume enclosed in the space habitat is used as a research facility to support deep space science related research and technology development. These applications focus on realizing space mining. However, other possible applications are not considered.

Kalam [26] discusses the application of space habitats in Mars exploration aiming at addressing the earth based challenge of energy security via lunar solar energy conversion. Lia *et al* [27] propose re-using space habitat technologies to realize solutions that address earth's challenges. This is suitable because space stations are designed to operate in a harsh environment. The relations between these motives are shown in Figure 1.

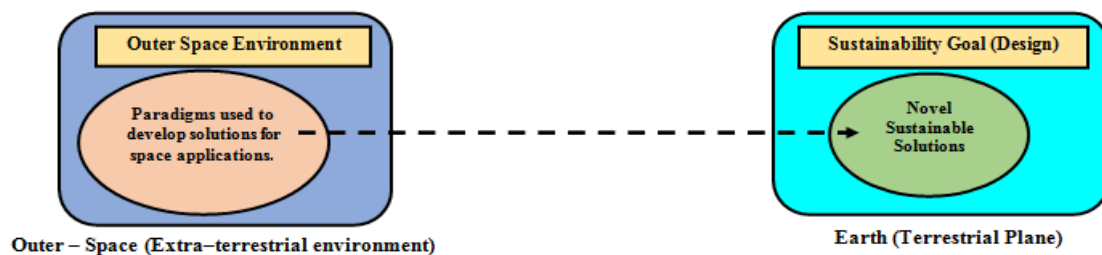


Figure 1: Role of space technologies in realizing sustainable solutions for earth based applications.

Space applications aim to leverage on space for human benefit [28–30]. In [29], SpaceX's satellite mega-constellation, OneWeb satellite mega-constellation, Telesat mega-constellation and the Amazon Kuiper mega-constellation are recognized applications that exploit space for wireless communications.

The applications in [28–30] exploit space technologies to realize space commercialization [31–34] and space continental initiatives [35]. Davis in [32] recognizes increasing private sector role in space commercialization. The discussion in [32] identifies and addresses regulatory space commercialization challenges. Current efforts in space commercialization largely targets communications and earth observations [29, 36].

Shammas *et al* in [36] examine space commercialization from the perspective of hosting more applications besides earth observations and communications. In addition, [36] note the increasing private sector in space supply provision and space mining. The applications in [36] exclude scientific experiments that focus on deriving knowledge from space related activities [37–38].

The increasing deployment of terrestrial cloud platforms is expected to process space data and support increased access of multi-media content and cloud services for wireless subscribers. This requires installing more high water footprint terrestrial data centres. A high water footprint reduces water availability for other applications. Data centres can be sited in locations like the stratosphere to reduce the water footprint. However, the siting of data centres in the stratosphere poses interference risks to radio astronomy. Such interference is similar to that posed by mega-constellation satellite networks [38–41]. The realization of a space habitat computing platform does not pose interference risks to radio astronomy.

Adams in [42] considers leveraging on the outer space environment aided by a nitrogen filled pod for realizing cooling and eliminating explosion hazards. The use of nitrogen has high costs. Moreover, the production of the nitrogen in [42] requires using earth's resources.

The use of computing platforms also enhances satellite data processing. Intelligent satellites are suitable as space edge computing nodes [43–44] that reduces satellite to computing platform transmission latency. Wang *et al* [19] describes capabilities enabling the use of satellites as edge nodes. The intelligent satellite is used in

edge computing to realize low latency data processing in satellite internet of things. The shift to space of edge nodes reduces the long term reliance on earth's resources. However, this perspective is not considered in [19].

Lai *et al* [43] propose a novel network that incorporates edge computing in geostationary networks. The space edge node is a geostationary satellite. Denby *et al* [44] propose the orbital edge computing. Orbital edge computing proposes collocating sophisticated processing hardware along sensors in small satellites. The discussion in [44] differentiates between cloud computing and edge nodes and recognizes that cloud platforms require backhaul network access. The discussion in [42–44] notes that siting data centres in space is appealing to computing. Research in [16, 19, 43–44] describes strategies explaining how edge computing enhances satellite network applications.

An alternative approach to accessing computing resources by space assets is presented in [45]. Straub *et al* [45] propose using space vehicle's idle computing resources by satellites for data processing. Space vehicles with idle computing resources constitute the space computing platform. A computing bottleneck occurs when space vehicles do not have sufficient resources to host external applications. The use of small satellite edge nodes can be used to resolve this bottleneck challenge.

However, Denby *et al* [44] point out that the availability of computing platforms can enhance data processing. Therefore, an absence of in-orbit computing platforms degrades space data processing. This can be addressed by increasing space segment computing resources. Therefore, space data processing via space computing platforms reduces water footprint, computing platform access latency and enhances accessible space segment computing resources.

2.3. Perspective of the Proposed Solution

The presented research aims to reduce the computing platform access latency, water footprint, and increase accessible computing resources. These challenges are addressed by siting data centres in space habitats.

3. Problem Description

The paper considers data centre operators seeking to process space data and site data centres near water sources. Let α be the set of terrestrial data centre operators.

$$\alpha = \{\alpha_1, \alpha_2, \dots, \alpha_A\} \quad (1).$$

The set of terrestrial data centres deployed by the α^{th} operator, $\alpha_a, \alpha_a \in \alpha$ is given by:

$$\alpha_a = \{\alpha_a^1, \alpha_a^2, \dots, \alpha_a^I\} \quad (2).$$

The cooling indicator of the i^{th} data centre from the α^{th} operator $\alpha_a^i, \alpha_a^i \in \alpha_a$ is denoted $I(\alpha_a^i) \in \{0,1\}$. The indicator values $I(\alpha_a^i) = 0$ and $I(\alpha_a^i) = 1$ signifies that data centre α_a^i is not and is water cooled respectively. In addition, let $\beta(\alpha_a^i, t_y), t_y \in t; t = \{t_1, t_2, \dots, t_Y\}$ be the water footprint of data centre α_a^i at the epoch t_y . Furthermore, let γ be the set of ground locations of terrestrial data centres.

$$\gamma = \{\gamma_1, \gamma_2, \dots, \gamma_B\} \quad (3).$$

The location indicator of data centre α_a^i at location $\gamma_b, \gamma_b \in \gamma$ at epoch t_y is denoted $I(\alpha_a^i, \gamma_b, t_y) \in \{0,1\}$. The data centre α_a^i is not located and is located at γ_b at epoch t_y when $I(\alpha_a^i, \gamma_b, t_y) = 0$ and $I(\alpha_a^i, \gamma_b, t_y) = 1$ respectively. The use of terrestrial data centres poses a challenge to water security when:

$$\sum_{a=1}^A \sum_{i=1}^I \sum_{b=1}^B \sum_{y=1}^Y I(\alpha_a^i) I(\alpha_a^i, \gamma_b, t_y) \beta(\alpha_a^i, t_y) \geq \sum_{b=1}^B w(\gamma_b) \quad (4).$$

Where $w(\gamma_b)$ is the amount of water resources available at the b^{th} terrestrial location γ_b .

Let ϕ be the set of applications requiring access to water resources such that:

$$\phi = \{\phi_1, \phi_2, \dots, \phi_C\} \quad (5).$$

In addition, let $w(\phi_c, \gamma_b)$; $\phi_c \in \phi$ be the water footprint of the c^{th} application ϕ_c at location γ_b . The demand for water by other application gives rise to water access challenges given the condition:

$$\left(\sum_{a=1}^A \sum_{i=1}^I \sum_{b=1}^B \sum_{y=1}^Y I(\alpha_a^i) I(\alpha_a^i, \gamma_b, t_y) \beta(\alpha_a^i, t_y) \right) + \left(\sum_{c=1}^C \sum_{b=1}^B w(\phi_c, \gamma_b) \right) \geq \sum_{b=1}^B w(\gamma_b) \quad (6).$$

The relation in (6) holds true under different conditions such as:

$$\left(\sum_{a=1}^A \sum_{i=1}^I \sum_{b=1}^B \sum_{y=1}^Y I(\alpha_a^i) I(\alpha_a^i, \gamma_b, t_y) \beta(\alpha_a^i, t_y) \right) > \left(\sum_{c=1}^C \sum_{b=1}^B w(\phi_c, \gamma_b) \right) \quad (7),$$

$$\left(\sum_{a=1}^A \sum_{i=1}^I \sum_{b=1}^B \sum_{y=1}^Y I(\alpha_a^i) I(\alpha_a^i, \gamma_b, t_y) \beta(\alpha_a^i, t_y) \right) \cong \left(\sum_{c=1}^C \sum_{b=1}^B w(\phi_c, \gamma_b) \right) \quad (8).$$

If (6) and (7) holds true, the data centre water footprint is less than that of other applications. The data centre water demand overwhelms water supply in the considered locations and is described as case C1. The case where (6) and (8) holds true is one in which data centre water footprint is roughly equal to that of other applications and is described as case C2. The water demand of data centres and existing applications jointly overwhelms the water supply source in cases C1 and C2. The discussion here reduces data centre water footprint.

Let ζ and ϑ be the set of small satellites and space vehicles requiring data processing respectively.

$$\zeta = \{\zeta_1, \zeta_2, \zeta_3, \dots, \zeta_D\} \quad (9),$$

$$\vartheta = \{\vartheta_1, \vartheta_2, \vartheta_3, \dots, \vartheta_E\} \quad (10).$$

Let $C_I(C_d, t_y)$ and $C_I(\vartheta_e, t_y)$, $\vartheta_e \in \vartheta$ be the amount of idle computing resources on-board the d^{th} small satellite C_d and the e^{th} space vehicle ϑ_e at epoch t_y respectively. The small satellite C_d hosts multiple applications such that:

$$\zeta_d = \{\zeta_d^1, \zeta_d^2, \dots, \zeta_d^F\} \quad (11).$$

The computing resources required to execute the f^{th} application $\zeta_d^f, C_d^f \in C_d$ at epoch t_y is denoted $C_1(C_d^f, t_y)$. Small satellites expected to process data have a challenge accessing computing resources when:

$$C3: \sum_{d=1}^D \sum_{f=1}^F \sum_{y=1}^Y C_1(\zeta_d^f, t_y) \geq \sum_{d=1}^D \sum_{y=1}^Y C_1(\zeta_d, t_y) \quad (12),$$

$$C4: \sum_{d=1}^D \sum_{f=1}^F \sum_{y=1}^Y C_1(\zeta_d^f, t_y) \geq \sum_{e=1}^E \sum_{y=1}^Y C_1(\vartheta_e, t_y) \quad (13),$$

$$C5: \sum_{d=1}^D \sum_{f=1}^F C_1(\zeta_d^f, t_y) < \sum_{d=1}^D \sum_{f=1}^F C_1(\zeta_d^f, t_{y+1}) < \sum_{d=1}^D \sum_{f=1}^F C_1(\zeta_d^f, t_{y+2}) \quad (14).$$

The conditions in C1–C2 describe challenges associated with reducing terrestrial data centres reliance on earth's water resources. The condition in C3, C4 and C5 describes challenges associated with accessing computing resources for processing small satellite data.

4. Proposed Solution

This section presents the solutions proposed to address the identified challenges. It has three parts. The first, second and third presents SHDCs network architecture, SHDC computing resource access (C3–C5) and asteroid water access in the SHDC (C1 – C2) respectively.

4.1 SHDC Network Architecture

The proposed solution reduces data centre demand on earth's water resources. Instead of realizing the data centre by integrating the storage and computing capabilities aboard small satellites, the use of a manned SHDC is proposed. The use of small satellites and space vehicles in a distributed architecture is suited for realizing edge nodes. However, it is challenging to upgrade computing payload after launch. Manned SHDCs support the upgrade of data centre computing payload or replace of damaged payload components.

The proposed SHDC comprises the cooling system (CLS), server and computing system (SCS) and the communication system (CCS). The CCS enables communications with space edge computing nodes, other SHDCs and ground stations. The CLS's coolant is asteroid water. This is feasible as meteorites and asteroids host water reservoirs [46–47]. Relation between the CLS, SCS, CCS and the earth segment is in Figure 2. The SCS receives workload from the terrestrial ground station gateway (TSGW) via the CCS. In Figure 2, the SHDC in low earth orbit (LEO) executes the workload received from space and terrestrial assets.

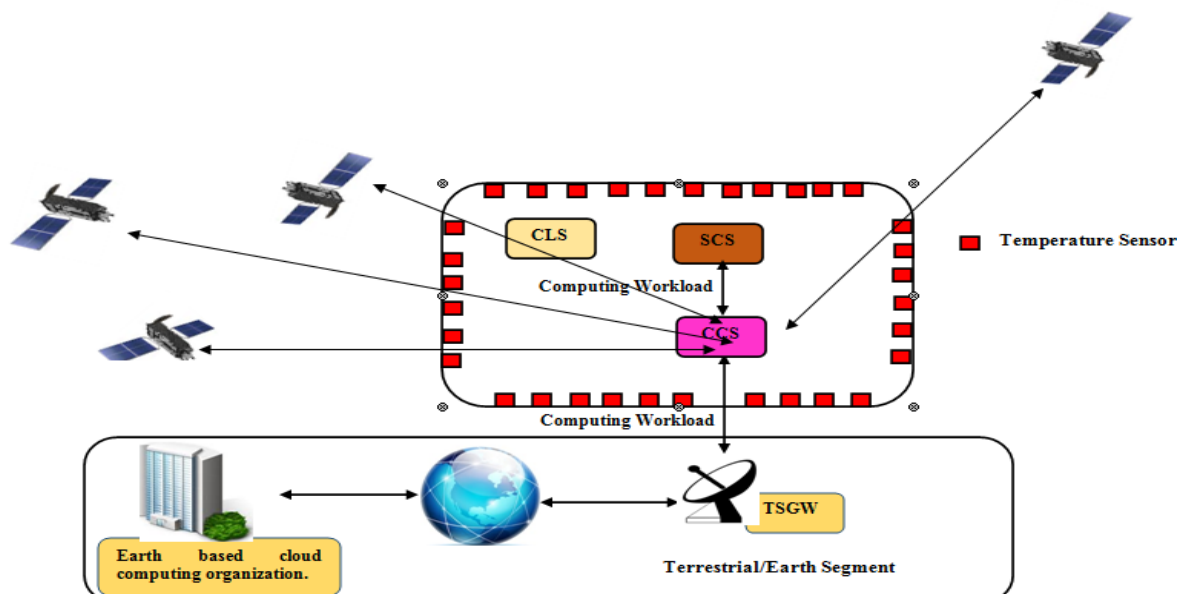


Figure 2: Relations between space habitat data centre, satellites and the terrestrial segment.

4.2 Proposed Solution – SHDC Access to Computing Resources

Inter-communication between SHDCs becomes necessary when SHDCs in the range of space vehicles or other SHDCs have insufficient computing resources as described in C3–C5. This can be addressed by increasing SHDC computing capability or launching more SHDCs. Let θ be the set of SHDCs.

$$\theta = \{\theta_1, \theta_2, \theta_3, \dots, \theta_f\} \quad (15).$$

The computing capability and idle computing resources of the j^{th} SHDC, $\theta_j, \theta_j \in \theta$ is denoted $C_1(\theta_j)$ and $C_I(\theta_j, t_y)$ respectively. The SHDC's mean idle computing resources is computed and shared with other SHDCs. The $(j + 1)^{th}$ SHDC $\theta_{j+1}, \theta_{j+1} \in \theta$ has the highest idle computing resources if:

$$\max \left(\sum_{y=1}^Y C_I(\theta_1, t_y), \dots, \sum_{y=1}^Y C_I(\theta_j, t_y), \sum_{y=1}^Y C_I(\theta_{j+1}, t_y) \right) = \sum_{y=1}^Y C_I(\theta_{j+1}, t_y) \quad (16).$$

The information on idle computing resources of other SHDCs is acquired by a SHDC and used to compute the average idle computing resources over a given duration. The received information is also used to rank SHDCs based on their idle computing resources. The process of accessing computing resources in an SHDC network is shown in Figure 3. If the SHDC does not have sufficient computing resources, the workload is fragmented and processed in a distributed manner in a SHDC network.

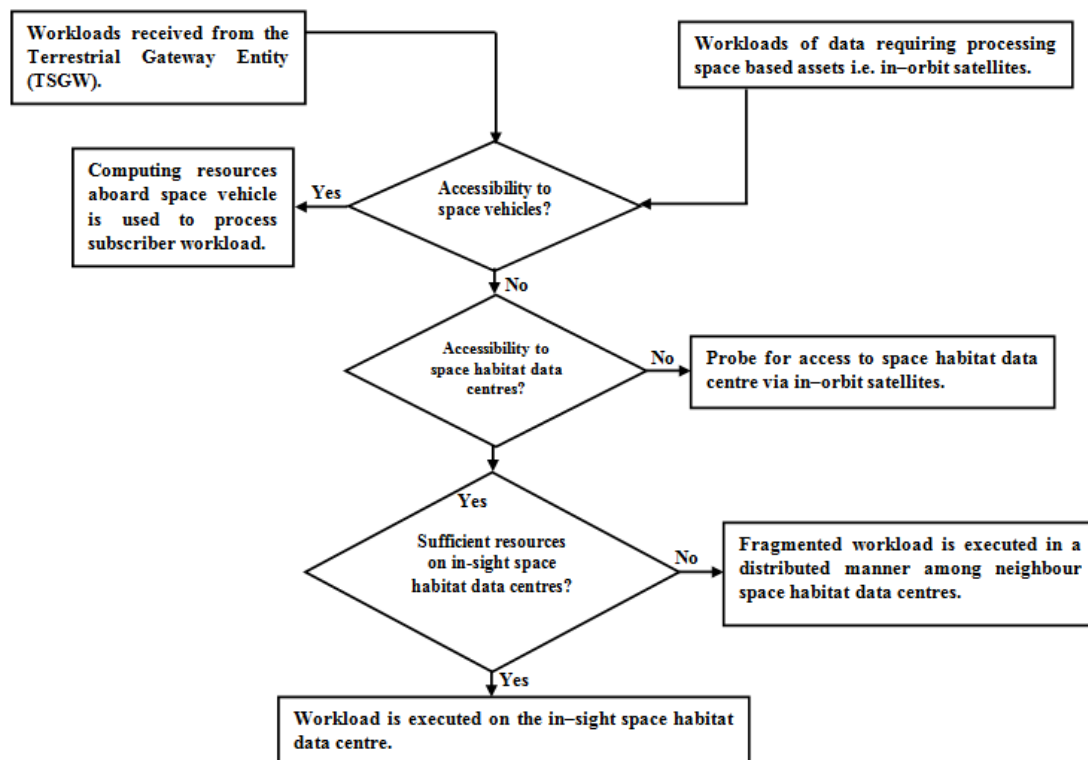


Figure 3: Steps in executing workload received from terrestrial TSGWs or space based in LEO satellites.

The SHDC intended for use in Figure 3 is hosted in an international computing space station with provider specific interfaces (PSIs). The PSIs enable computing platform service providers to host data centres in the space habitat. The CLS, SCS and CCS are present in each SHDC. PSIs are attached to the international computing space station via space computing nodes (SCNs). The role of PSIs, SCNs, computing and algorithm execution entities is shown in Figure 4. Each data centre comprises a PSI through which subscribers' access computing services via the CCS. Figure 4 has 8 PSIs. The concerned PSIs is given as PSI x , $x = \{1,2,3,4,5,6,7,8\}$ and are attached to the subsystem monitoring chambers via the SCNs. SCNs host sensors and enable data transfer from the PSI to the subsystem monitoring chambers.

The architecture also shows sub-components supporting SHDC functioning. These are the living space for data centre engineers, store, and subsystem monitoring chambers. The subsystem monitoring chamber hosts components that monitor data centre performance and water availability for SHDC cooling. The store hosts the spare sub-systems and devices. It is allocated to different organizations and can be replenished by trips to the

international computing space station. Each PSI communicates with ground based entities and satellites via the CCS. The SHDC’s computing payload is operated by the engineers in the living space. The engineers execute maintenance procedures in a manner similar to terrestrial data centers.

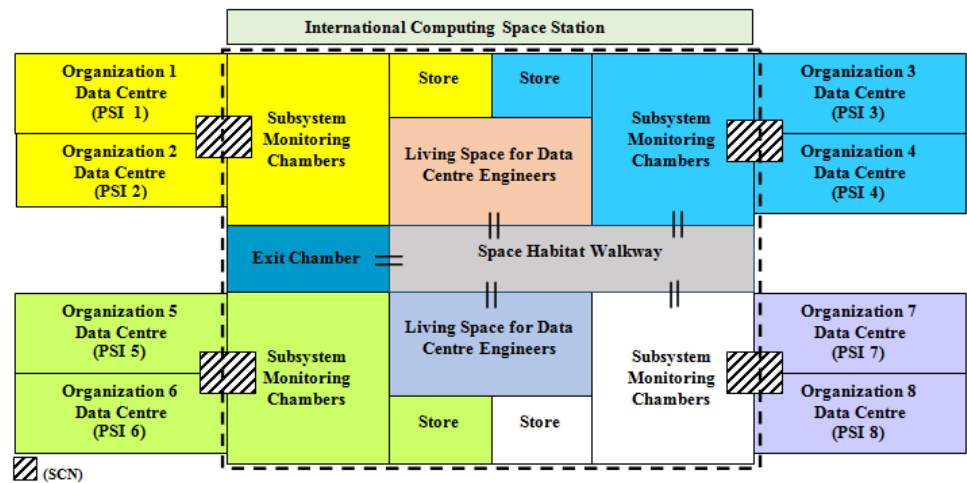


Figure 4: Relations between PSIs, SCNs and entities in the international computing space station.

4.3 SHDC – Supplying Asteroid Water

The SHDC requires access to asteroid water for cooling. The supply of asteroid water involves three entities i.e. space water reservoir entity (SWRE), asteroid water mining entity (AWME) and the computing platform service provider. The SWRE and AWME can also supply water to other outer space applications that require access to water and products that can be directly derived from water. Examples of such are space applications requiring the provision of hydrogen fuel for space based applications as seen in [48].

The SWRE receives information on SHDC location, stores and supplies asteroid water to the SHDC via water supply vehicles. This reduces the asteroid water supply delay in comparison to the case where asteroid water is mined and directly supplied to the SHDC. Relations between the AWME, SWRE and SHDC are shown in Figure 5. The flowchart showing SWRE and SWR functionality is shown in Figure 6.

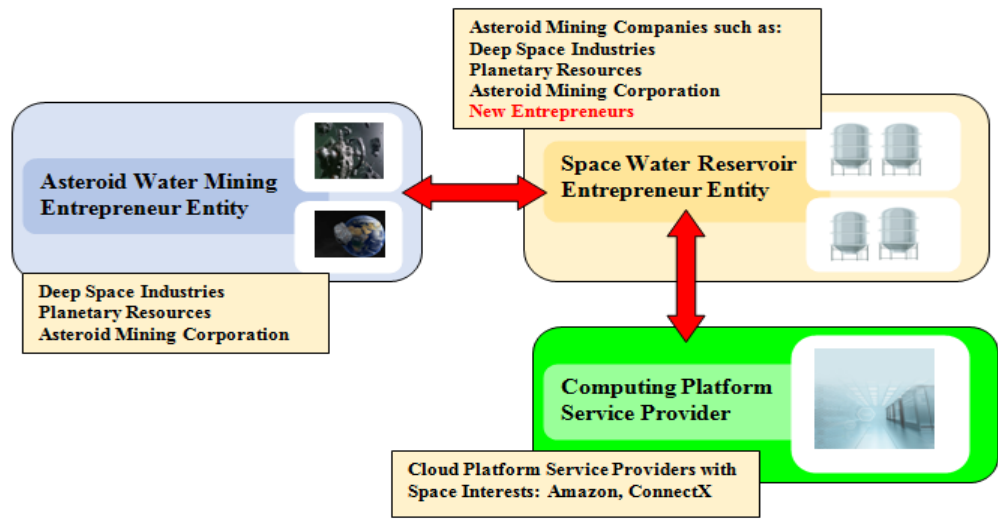


Figure 5: Relations between AWME, water storage and access by platform service providers.

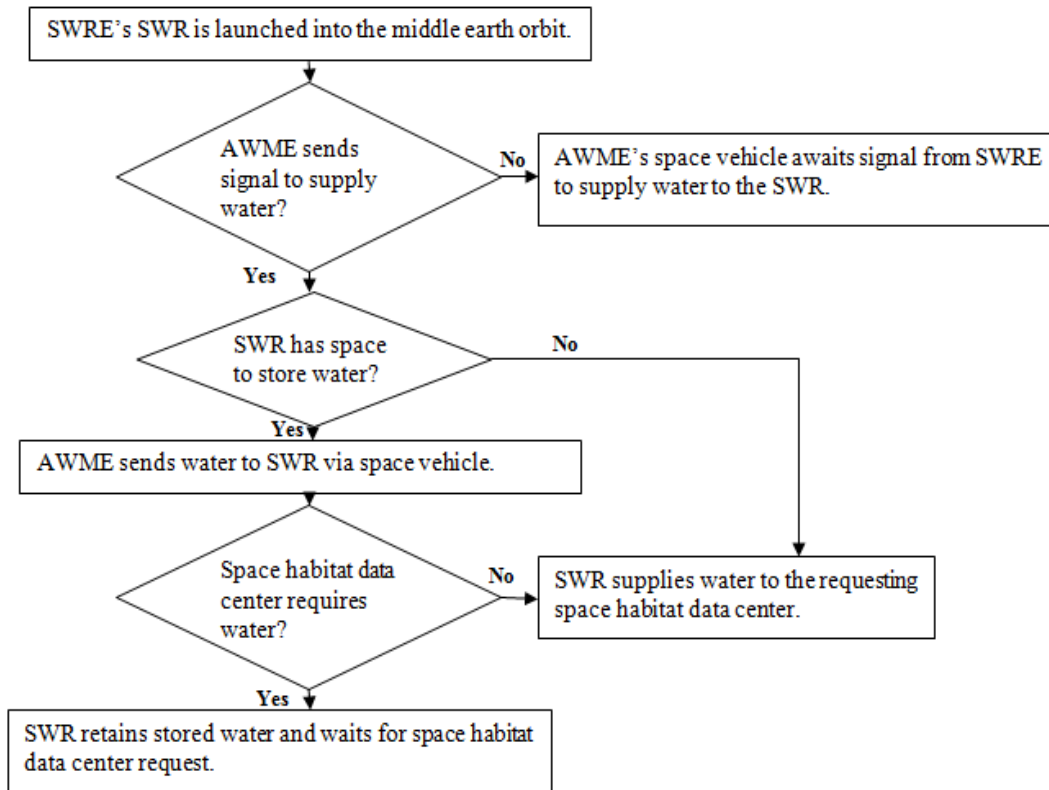


Figure 6: Relations between AWME, SWRE and SWR in the supply of asteroid water for the SHDC.

5. Performance Formulation

The performance model assumes that small satellites have limited computing capability necessitating accessing additional computing resources. In existing work [19, 44], the data requiring processing is transmitted to the terrestrial cloud computing platform. The formulated metrics are the computing platform access latency and the accessible computing resources in the space segment. This section has two parts. The first and second parts formulate cloud platform access latency and accessible computing resources in the space segment respectively.

5.1 Computing Platform Access Latency

The small satellite ζ_d can access computing resources computing platforms sited in different locations i.e. terrestrial, stratosphere or space (i.e SHDC). Let $\mathcal{F}$ be the set of stratosphere based computing platforms:

$$\mathcal{F} = \{\mathcal{F}_1, \mathcal{F}_2, \dots, \mathcal{F}_V\} \quad (17).$$

The altitude of the small satellite C_d , SHDC θ_j , space vehicle, ϑ_e stratosphere based computing platform $\mathcal{F}_z, \mathcal{F}_z \in \mathcal{F}$ are $h(C_d), h(\theta_j), h(\vartheta_e)$ and $h(\mathcal{F}_z)$ respectively. In addition, let $Th(C_d, q, t_y), q \in \{\theta_j, \mathcal{F}_z, \vartheta_e, \alpha_a^i\}$ denote the link speed between the small satellite and computing platform entity q at the epoch t_y . The amount of data from small satellite C_d requiring access to computing resource aboard the computing platform entity q is denoted $D(C_d, t_y)$. The computing platform access latency for stratosphere computing platforms, Γ_1 is given as:

$$\Gamma_1 = \sum_{y=1}^Y \sum_{z=1}^V \sum_{d=1}^D \left(\frac{D(\zeta_d, t_y)}{Th(\zeta_d, \mathcal{F}_z, t_y)} + \frac{(h(\zeta_d) - h(\mathcal{F}_z))}{3 \times 10^8} \right) \quad (18),$$

It is also feasible that the small satellite accesses a stratosphere computing platform via other stratosphere computing platforms through inter-platform links. This is necessary when small satellite has transmit power constraints. The compute resource (or platform) access latency Γ_1' is given as:

$$\Gamma_1' = \sum_{y=1}^Y \sum_{u=1}^U \sum_{d=1}^D \left(\frac{D(C_d, t_y)}{Th(C_d, f_u, t_y)} + \frac{D(f_u, f_{u+x}, t_y)}{Th(f_u, f_{u+x}, t_y)} + \frac{(h(C_d) - h(f_z))}{3 \times 10^8} + \frac{|h(f_u) - h(f_{u+x})|}{3 \times 10^8} \right) \quad (19),$$

$$f_u \in f, f_{u+x} \in f, f_u \neq f_{u+x}.$$

$D(f_u, f_{u+x}, t_y)$ and $Th(f_u, f_{u+x}, t_y)$ are the size of data transmitted and inter-platform link speed between the u^{th} and $(u+x)^{th}$ stratosphere computing platforms at the epoch t_y respectively.

$h(f_u)$ and $h(f_{u+x})$ are the altitude of the u^{th} and $(u+x)^{th}$ stratosphere computing platforms respectively.

The compute resource access latency for the terrestrial cloud computing platforms Γ_2 is given as:

$$\Gamma_2 = \sum_{y=1}^Y \sum_{i=1}^I \sum_{d=1}^D \left(\frac{D(C_d, t_y)}{Th(C_d, \alpha_a^i, t_y)} + \frac{(h(C_d))}{3 \times 10^8} \right) \quad (20).$$

It is also feasible that the small satellite accesses the terrestrial cloud computing platform via high altitude platform (HAP). This becomes necessary when there is transmit power limitation aboard small satellites. The compute resource access delay, Γ_2' and given as:

$$\Gamma_2' = \sum_{y=1}^Y \sum_{a=1}^A \sum_{d=1}^D \sum_{z=1}^Z \left(\left(\frac{D(C_d, f_z, t_y)}{Th(C_d, f_z, t_y)} + \frac{D(f_z, \alpha_a^i, t_y)}{Th(f_z, \alpha_a^i, t_y)} \right) \right) + \left(\frac{(h(C_d))}{3 \times 10^8} \right) \quad (21).$$

$Th(f_z, \alpha_a^i, t_y)$ is the link throughput between the stratosphere cloud platform f_z and the i^{th} terrestrial cloud platform of the a^{th} operator.

$D(C_d, f_z, t_y)$ and $D(f_z, \alpha_a^i, t_y)$ are the size of data transmitted from the small satellite to the HAP and from the HAP to the terrestrial data center respectively.

The parameters Γ_1 , Γ_1' , Γ_2 and Γ_2' describe the latency associated with computing resource access latency in the context of existing work. Terrestrial cloud computing platform access is supported in [19, 44] when small satellites have compute resource constraints. In the proposed scheme, small satellites access idle computing resources on space vehicles and the SHDC. Let Γ_3 and Γ_4 denote the compute resource access delay for the space vehicle and the SHDC.

$$\Gamma_3 = \sum_{y=1}^Y \sum_{e=1}^E \sum_{d=1}^D \left(\frac{D(C_d, t_y)}{Th(C_d, \vartheta_e, t_y)} + \frac{|h(C_d) - h(\vartheta_e)|}{3 \times 10^8} \right) \quad (22),$$

$$\Gamma_4 = \sum_{y=1}^Y \sum_{j=1}^J \sum_{d=1}^D \left(\frac{D(C_d, t_y)}{Th(C_d, \theta_j, t_y)} + \frac{|h(C_d) - h(\theta_j)|}{3 \times 10^8} \right) \quad (23).$$

The scenarios in Γ_3 and Γ_4 do not consider the context where data is forwarded from the space vehicle to the SHDC. This is feasible when a new SHDC is deployed and it is necessary to transmit data from the space vehicle to the SHDC. In this case, the compute resource access latency is denoted Γ_4' and given as:

$$\Gamma_4' = \sum_{d=1}^D \sum_{e=1}^E \sum_{j=1}^J \sum_{y=1}^Y \left(\frac{D(C_d, t_y)}{Th(C_d, \vartheta_e, t_y)} \right) + \left(\frac{D(\vartheta_e, \theta_j, t_y)}{Th(\vartheta_e, \theta_j, t_y)} \right) + \left(\frac{|h(C_d) - h(\vartheta_e)|}{3 \times 10^8} \right) + \left(\frac{|h(\theta_j) - h(\vartheta_e)|}{3 \times 10^8} \right) \quad (24).$$

5.2 Accessible Computing Resources in Space Segment

The use of SHDCs increases accessible space segment computing resources. In existing mechanism [19], the small satellite's computing resources are used. In the case of orbital edge computing, the accessible computing resources is denoted C_{ra}^1 and given as:

$$C_{ra}^1 = \sum_{y=1}^Y \left(\left(\sum_{d=1}^D C_I(C_d, t_y) \right) + \left(\sum_{g=1}^G C_I(C_g', t_y) \right) \right) \quad (25).$$

$C_I(C_g', t_y)$ is the amount of idle computing resources aboard other LEO satellites used for applications besides orbital edge computing.

The small satellites used in orbital edge computing can also utilize the idle computing resources aboard satellites used in other applications. The total amount of accessible computing resources given that small satellites and space vehicles provide computing resources is denoted C_{ra}^2 and given as:

$$C_{ra}^2 = \sum_{y=1}^Y \left(\left(\sum_{d=1}^D C_I(C_d, t_y) \right) + \left(\sum_{g=1}^G C_I(C_g', t_y) \right) + \left(\sum_{d=1}^D C_I(\vartheta_e, t_y) \right) \right) \quad (26).$$

In the event that space vehicles and SHDCs provide access to computing resources, the total amount of accessible computing resources is denoted C_{ra}^3 and given as:

$$C_{ra}^3 = \sum_{y=1}^Y \left(\left(\sum_{j=1}^J C_I(\theta_j, t_y) \right) + \left(\sum_{d=1}^D C_I(\vartheta_e, t_y) \right) \right) \quad (27).$$

6. Feasibility and Performance Evaluation

This section discusses feasibility, evaluation results and has two parts. The first and second part presents results on feasibility of accessing asteroid water for SHDC cooling and analysis of performance benefits in the quality of service (QoS) respectively.

6.1 Feasibility of Accessing Asteroid Water Resources

This section presents asteroids whose water can be used for cooling SHDCs. Water bearing asteroid data is obtained from [49], analyzed and presented in Table I. Analysis examines the feasibility of mining water from asteroids for a twenty-year period as shown in Table II. The maximum, minimum and mean access intervals are 690 days and 81 days and 319.39 days respectively. In Table II, the access interval is in the format $[x; y]$ for dates $[a, b, c]$. x and y are the number of days between dates a and b and dates b and c respectively.

Table I: List of water bearing asteroids and the near earth approach dates.

s/n	Name	Near Earth Approach Dates
1	1991 DB	Mar 6, 2027, Feb 29, 2036; June 17, 2083 - 3 Approaches
2	Seleucus	Mar 24, 2037, Apr 06, 2040; May 8, 2069; Mar 27, 2072–4 Approaches
3	1998 KU2	Oct 15 2025, Jul 31 2042, Sept 18 2069, June 28 2086, Oct 18 2096–5 Approaches
4	2001 PD 1	Oct 03 2021, Sept 23 2031, Sept 01 2041, Nov 01 2118 –4 Approaches
5	1992 NA	Oct 27 2029, Aug 14 2055, Oct 25 2066, Oct 12 2092, Aug 08 2118–5 Approaches
6	2002-AH29	Jan 19 2032, Apr 02 2047, Apr 06 2062, Jan 28 2092, Feb 19 2107–5 Approaches
7	David-Harvey	Dec 16 2033, Dec 10 2072, Dec 17 2111 – 3 Approaches
8	1999 VN6	Nov 27 2031, Nov 22 2047, Nov 25 2056, Dec 01 2072, Dec 01 2088, Nov 30 2104 – 6 Approaches.
9	2001 XS 1	Dec 08 2049, Dec 08 2097–2 Approaches
10	2001 SJ262	Oct 17 2057, Oct 06 2062, Oct 14 2103–3 Approaches
11	1997AQ 18	May 11 2022, Dec 21 2023, Aug 16 2028, Jun 14 2033, Dec 16 2034, May 01 2038, Sep 30 2039, Jul 31 2044, Dec 30 2045, May 31 2049, Dec 14 2050, Apr 26 2054, Sep 18 2055, Jan 5 2056, Jul 24 2060, Dec 28 2061, May 27 2065, Dec 14 2066, Apr 26 2070, Sept 18 2071, Jan 05 2072, Jul 27 2076, Dec 29 2077, Jun 01 2081, Dec 15 2082, Apr 30 2086, Sept 28 2087, Jan 01 2088, Aug 06 2092, Dec 17 2098, May 07 2102 – 31 Approaches
12	2002 DH2	Jul 06 2046, Apr 08 2049, Mar 10 2052, Feb 22 2055, Jul 06 2108 – 5 Approaches
13	Betulia	Jun 07 2028, May 08 2090, May 13 2103 – 3 Approaches
14	Sigurd	Oct 12 2022, Sept 18 2027, Aug 07 2032, Oct 02 2045, Aug 30 2050, Sept 20 2068, Aug 19 2073,Oct 15 2086, Sep 09 2091, Aug 08 2096, Sep 30 2109 –11 Approaches
15	1991XB	Nov. 30 2067, Nov 28 2118 – 2 Approaches
16	2000-YO-29	Dec 24 2027, Jun 10 2040, Dec 26 2049, Jun 17 2062, Dec 28 2071, Jun 21 2084, Dec 29 2093, Jun 26 2106, Dec 31 2115 – 8 Approaches

Table II: Access dates and intervals for water bearing asteroids.

s/n	Access Dates	Access Intervals	Access Dates	Access Intervals
1	Oct 03 2021	[248 ; 181]	Nov 27 2031	[81 ; 227]
2	May 11 2022		Jan 19 2032	
3	Oct 12 2022	[435 ; 688]	Aug 07 2032	[322 ; 212]
4	Dec 21 2023		June 14 2033	
5	Oct 15 2025	[536 ; 223]	Dec 16 2033	[390 ; 469]
6	Mar 6, 2027		Dec 16 2034	
7	Sep 18 2027	[127 ; 192]	Feb 29 2036	[414; 431]
8	Dec 24 2027		Mar 24 2037	
9	Jun 07 2028	[100 ; 437]	May 01 2038	[539 ; 215]
10	Aug 16 2028		Sep 30 2039	
12	Sept 23 2031		Apr 06 2040	95
			June 10 2040	

6.2 Performance Evaluation and Benefits – Compute Resource Related QoS

This section present and discusses the results on the performance evaluation from the perspective of the compute resource related QoS. This is done using values in Table III. The link speed is of the order of Gigabits per second and Megabits per second. This range of values is considered feasible for realistic satellite communications as seen in [50]. Furthermore, the size of satellite data is of the order of Kilobytes and Megabytes. This is also considered feasible for satellite applications as seen in [50].

Table III: Compute Resource Access Latency Simulation Parameters.

S/N	Parameter	Value
1	Number of satellites in space segment	10
2	Number of epochs	15
3	Maximum Size of Data – Satellite [1 2 3 4 5]	[1.48 , 1.47 , 1.25 , 1.33 , 1.45] Mbytes
4	Maximum Size of Data – Satellite [6 7 8 9 10]	[1.42, 1.47, 1.41 , 1.46, 1.33] Mbytes
5	Minimum Size of Data – Satellite [1 2 3 4 5]	[1.04, 148.9, 353.6, 317.9 , 852.81] Kbytes
6	Minimum Size of Data – Satellite [6 7 8 9 10]	[12.37, 82.31, 92.30, 113.00, 6.71] Kbytes
7	Mean Size of Data – Satellite [1 2 3 4 5]	[866.37,777.78,567.04,917.37,811.12] Kbytes
8	Mean Size of Data – Satellite [6 7 8 9 10]	[718,665.93, 920.20, 844.61, 763.45] Kbytes
9	Maximum Link Speed – Satellite [1 2 3 4 5]	[2.99, 2.98 , 2.92, 2.93, 2.68] Gbps
10	Maximum Link Speed – Satellite [6 7 8 9 10]	[2.82 , 2.73 , 2.69 , 2.76 , 2.83] Gbps
11	Minimum Link Speed – Satellite [1 2 3 4 5]	[380.17, 380.57, 930, 280.8, 124.44] Mbps
12	Minimum Link Speed – Satellite [6 7 8 9 10]	[32.67, 237.97, 776.48, 107.31,156.90] Mbps
13	Mean Link Speed – Satellite [1 2 3 4 5]	[1.47 , 1.87, 2.01, 1.69, 1.28] Gbps
14	Mean Link Speed – Satellite [6 7 8 9 10]	[1.395 , 1.49 , 1.26 , 1.25 , 1.35] Gbps
15	Altitude – Satellite [1 2 3 4 5]	[780.5 , 791.0 , 711.6 , 631.04 , 766.63] km
16	Altitude – Satellite [6 7 8 9 10]	[798.7 , 760.4 , 614.1 , 574.4 , 759.9] km
21	Number of Space Habitat Data Centers	3
22	Space Habitat Data Center Altitude –[1 , 2 , 3]	[921.1 , 252.5 , 383.7] km
23	Number of High Altitude Platforms	4
24	High Altitude Platform Altitude (Mesosphere)–[1 , 2 , 3 , 4]	[25.4 74.1, 67.5, 71.9] km
25	Size of Data Transmitted by High Altitude Platforms–[1 , 2 , 3 , 4]	[1.4 0.997 0.45 1.96] Mbps
26	Inter – High Altitude Platform Link Speed	[1.92 , 0.69 , 0.08] Mbps

The compute resource access latency is evaluated for the existing scheme without and with use of forwarding links. The compute resource access latency (compute platform access latency) for terrestrial data centers, stratosphere based data centers and the SHDC without forwarding links is shown in Figure 7. Analysis shows that using HAP computing platforms and SHDC instead of terrestrial computing platform reduces the compute resource access latency by 11.9% and 33.6% on average respectively. In addition, accessing the SHDC instead of HAP computing platforms reduces compute resource access latency by 24.5% on average.

The results in Figure 8 and Figure 9 show the forwarding latency when the HAP computing platform and terrestrial computing platforms is accessed through HAP forwarding links respectively. Results in Figures 8 and 9 shows that the forwarding latency increases with forwarding HAPs. Analysis of results in Figure 8 and Figure 9 shows that increasing the number of forwarding HAPs from 1 to 3, 1 to 2 and 2 to 3 increases the forwarding latency by {96.1%, 61.3 % , 90%} and { 44.7%, 35.6%, 14.2% } on average respectively. The use of the SHDC instead of HAP and terrestrial data centers via forwarding reduces the computing platform access latency Extensive simulations show that the compute resource access latency is reduced by up to 98.5% on average.

Evaluation also investigates how the use of SHDCs enhances space segment accessible computing resources. The simulation uses test SHDCs hosting a limited number of servers and 5 LEO space vehicles. Two space vehicles are utilized for executing algorithms and processing data related to space astronomy. Three LEO SHDCs (each with three servers) are considered. The utilized values are in Table IV. The investigation of accessible computing resources for the existing scheme is done considering two cases. In the first case, the existing orbital edge computing [19] is considered.

The second case is one in which the computing resources on space vehicles are accessed in to that in existing orbital edge computing.

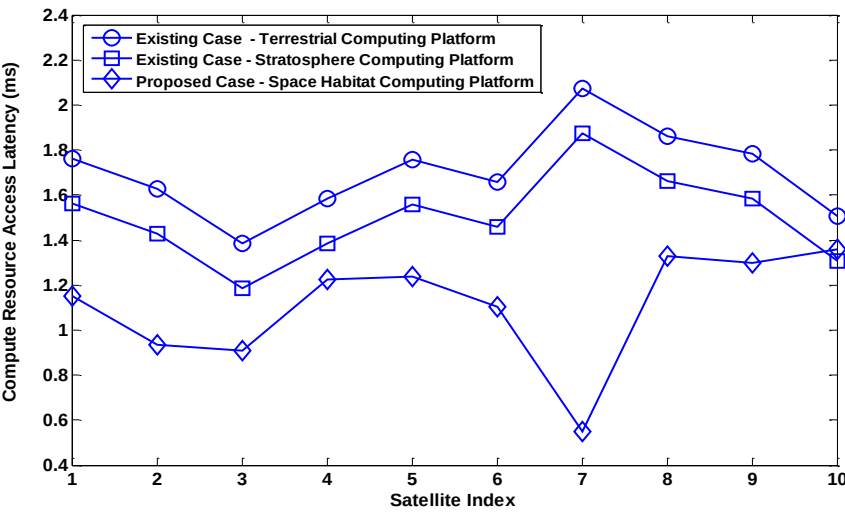


Figure 7: Simulation results for the compute resource access latency for existing and proposed cases.

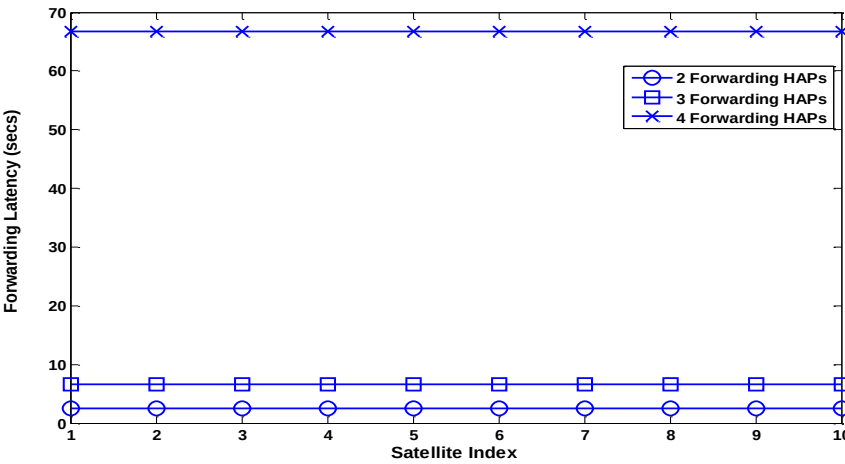


Figure 8: Simulation results for the forwarding latency in the case of accessing HAPs.

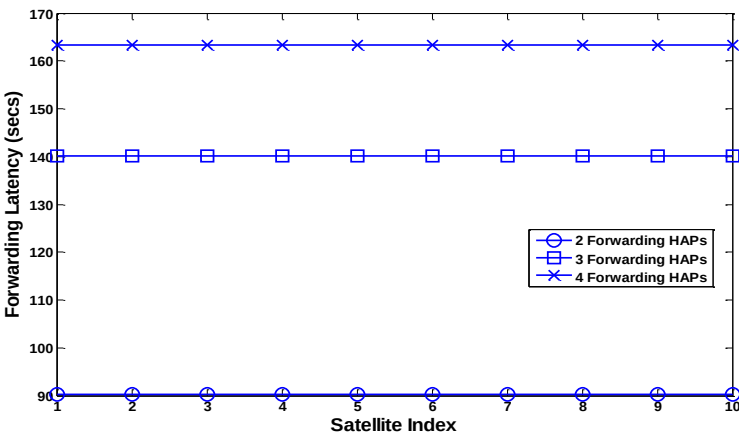
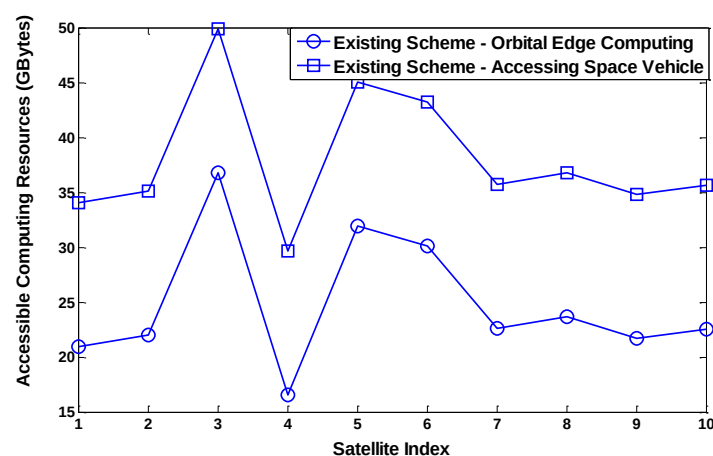


Figure 9: Forwarding latency when accessing terrestrial computing platforms by forwarding through HAPs.

Table IV: Simulation Parameters for Investigating Accessible Computing Resources.

S/N	Parameter	Value
1	Number of Satellites	10
2	Number of Epochs	15
3	Number of Space Vehicles and Space Habitat Data Centers	5, 3
4	Maximum Satellite Computational Resources [1, 2, 3, 4, 5]	[85.7, 90.2, 97.7, 97.2, 96.9] GBytes
5	Maximum Satellite Computational Resources [6, 7, 8, 9, 10]	[96.2, 94.0, 84.8, 90.7, 88.7] GBytes
6	Minimum Satellite Computational Resources [1, 2, 3, 4, 5]	[1, 1.76, 13.9, 0.32, 4.94] GBytes
7	Minimum Satellite Computational Resources [6, 7, 8, 9, 10]	[7, 1.102, 1.27, 0.45] GBytes
8	Mean Computational Resources on Satellites [1, 2, 3, 4, 5]	[52.6, 52.4, 58.4, 39.2, 61.3] GBytes
9	Mean Computational Resources on Satellites [6, 7, 8, 9, 10]	[50.3, 38.7, 43.2, 39.3, 57.0] GBytes
10	Number of servers on Space Habitat Data Centers 1, 2, 3	3 Servers per SHDC
11	Computing Capability of Servers on SHDC 1- [1, 2, 3]	[65.5, 22.3, 50.1] GBytes
12	Computing Capability of Servers on SHDC 2- [1, 2, 3]	[43.9, 24.3, 40.8] GBytes
13	Computing Capability of Servers on SHDC 3- [1, 2, 3]	[11.0, 5.7, 42.0] GBytes
14	Compute utilization of Servers on SHDC 1- [1, 2, 3]	[36.3%, 21.3%, 7%]
15	Compute utilization of Servers on SHDC 2- [1, 2, 3]	[47.7%, 72.5%, 24.8%]
16	Compute utilization of Servers on SHDC 3- [1, 2, 3]	[18.8%, 5.2%, 43.6%]
17	Compute Resources on Space Vehicles – [1, 2, 3, 4, 5]	[49.8, 32.6, 72.2, 7.5, 51.1] GBytes
18	Space Vehicle 1 Fully utilized (No computing resources)	Yes
19	Space Vehicle 2 Fully utilized (No computing resources)	Yes
20	Space Vehicle 3 Fully utilized (No computing resources)	No
21	Space Vehicle 4 Fully utilized (No computing resources)	No
22	Space Vehicle 5 Fully utilized (No computing resources)	No
23	Compute Resource Utilization on Space Vehicles – [3, 4, 5]	[63.8%, 37.2%, 28.8%]

The result of the accessible computing resources is shown in Figures 10 and 11. The simulation also investigates how the use of up to two SHDCs enhances accessible computing resources. The result in this case is shown in Figure 11. Analysis shows that using one SHDC and two SHDCs instead of existing scheme without and with space vehicles increases accessible computing resources by {65.3%, 46.7%} and {77%, 64.7%} on average respectively. In addition, increasing the number of SHDCs from one to two improves accessible computing resources by 33.8% on average.

**Figure 10:** Accessible Computing Resources in the case of orbital edge computing and space vehicles.

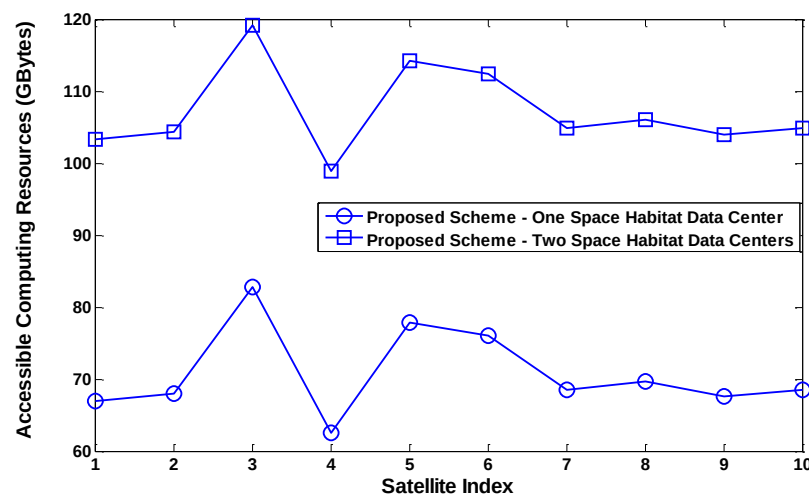


Figure 11: Accessible Computing Resources considering the use of up to two space habitat data centers.

7. Conclusion

The discussion proposes solutions to reduce the high water footprint for cloud data centres and sites data centres in space habitats. The space habitat data center is cooled using water mined from asteroids. The feasibility of using space habitat data centers is studied by asteroids with water content. Data analysis shows that water from asteroids can be accessed once a year. The use of space habitat data centers also increases the accessible computing resource in the space segment.

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Reference

1. M. Avgerinou, P. Bertoldi and L. Castellazi, ‘Trends in Data Centre Energy Consumption under the European code of conduct for data centre energy efficiency’, *Energies*, 2017, 10, 1470, pp 1 – 18.
2. R. Hintemann and S. Hinterholzer, ‘Energy consumption of data centers worldwide – How will the internet become green?’ 6TH International Conference on ICT for Sustainability, Lappeenranta, Finland, June 10 – 14, 2019, Paper 16.
3. C. Coroner, M. Ashman and L. J. Nilsson, ‘Data Centres in Future European Energy Systems – energy efficiency, integration and policy’, *Energy Efficiency*, 13, 2020, pp 129 – 144.
4. P. Wang, Y. Cao and Z. Ding, ‘Resources planning strategies for data centre micro-grid considering water footprints’, *IEEE Conference on Energy Internet and Energy System Integration*, 20 – 22 Oct 2018, Beijing China, pp 1 – 6.
5. A. Capozzoli and G. Primiceri, ‘Cooling Systems in Data Centers: state of art and emerging technologies’, *Energy Procedia*, Vol. 83, 2015, PP 484 – 493.
6. Amazon, ‘Reducing water used for cooling in AWS Data centers’, [Online] Available: <https://aws.amazon.com/about-aws/sustainability/>
7. S. Flucker, R. Tozer and B. Whitehead, ‘Data Centre sustainability – Beyond energy efficiency’, *Building Services Engineering Research and Technology*, Vol. 39, N. 2, pp 173 – 182.
8. S. Taheri, M. Goudarzi and O. Yoshie, ‘Learning – based power prediction for geo-distributed data centres: Weather Parameter analysis’, *Journal of Big Data*, 7(8), 2020, pp 1 – 16.

9. Y. Li, Y. Wen, K. Guan and D. Tao, 'Transforming cooling optimization for Green Data Center via Deep Reinforcement Learning', *IEEE Transactions on Cybernetics*, 25 July 2019, Early Access, pp 1 – 12.
10. C. Gough, I. Steiner and W.A. Saunders, 'Data center management', in 'Energy Efficient Servers: Blueprints for Data Center Optimization – The IT Professional's operational handbook', pp 307 – 318, April 2015.
11. Y. Zhang, Z. Wei and M. Zhang, 'Free cooling technologies for data centres: energy saving mechanism and applications', *Energy Procedia*, Vol. 143, 2017, pp 410 – 415.
12. D.V. Le, Y. Li, R. Wang, R. Tan, Y. Wong and Y. Wen, 'Control of Air Free – Cooled Data Centers in Tropics via Deep Reinforcement Learning', 6TH ACM International Conference on Systems for Energy - Efficient Buildings, Cities and Transportation (BuildSys'19), Nov 13 – 14, 2019.
13. A. Periola, 'Incorporating diversity in cloud – computing: a novel paradigm and architecture for enhancing the performance of future cloud radio access networks', *Wireless Networks*, Vol.25, No. 7, 2019, pp 3783 – 3803.
14. AA Periola, AA Alonge and KA Ogudo, 'Architecture and System Design for Marine Cloud Computing Assets', *The Computer Journal*, Feb 2020, Vol. 63, No. 6, 2020, pp 927 – 941.
15. B. Cutler, S.G. Fowers, J. Kramer and E. Peterson, 'Dunking the data center', *IEEE Spectrum*, Vol. 54, No. 3, March 2017, pp 26 – 31.
16. H. Huang, S. Guo and K. Wang, 'Envisioned Wireless Big Data Storage for Low Earth Orbit Satellite Based Cloud', *IEEE Wireless Communications*, Vol. 25, No. 1, Feb 2018, pp 26 – 31.
17. AA Periola and MO Kolawole, 'Space Based Data Centres: A Paradigm for Data Processing and Scientific Investigations', *Wireless Personal Communications*, Vol. 107, 2019, pp 95 – 119.
18. A. Donoghue, 'The Idea of Data Centers in Space Just got a little less crazy', [Online] Available: <https://www.datacentreknowledge.com/edge-computing/idea-data-centers-space-just-got-little-less-crazy/>, Feb 09 2019, Accessed 01/03/2020.
19. Y. Wang, J. Yang, X. Guo and Z. Qu, 'Satellite Edge Computing for the Internet of things in Aerospace', *Sensors*, Oct 2019, 4375, pp 1 – 16.
20. P.Calla, D.Fries, and C.Welch, 'Asteroid mining with small spacecraft and its economic feasibility' arXiv, [online] available: <https://arxiv.org/pdf/1808.05099.pdf>
21. A. MacDonald, 'Emerging Space – The Evolving Landscape of 21ST Century American Spaceflight', [Online] Available <https://www.nasa.gov/sites/default/files/files/EmergingSpacePresentation20140829.pdf>, April 2014.
22. V. Yakolev, 'Mars Terraforming – The Wrong Way', *Planetary Science Vision 2050 Workop 2017 (LP1 Contribution No. 1989)*.
23. D. Smitherman, and B. Griffin, 'Habitat Concepts for Deep Space Exploration', *AIAA Space 2014, Conference and Exposition, AIAA 2014-4477*, San Diego, CA, 2014.
24. B.N. Griffin, R.Lewis and D. Smitherman, 'SLS – Derived Lab: Precursor to Deep Space Human Exploration', *AIAA Space 2015 Conference and Exposition*, 31 Aug – 2 Sept, 2015, Pasadena, California, <https://doi.org/10.2514/26.2015-4453>.
25. D.V. Smitherman, D.H. Needham and R. Lewis, 'Research Possibilities beyond the deep space gateway', *Deep Space Gateway Science Workshop*, 27 Feb - 1 March 2018, LPI Contrib No. 2063, [Online] ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180002054.pdf
26. A.P.J. Abdul Kalam, 'The future of Space Exploration and Human Development', *The Pardee Papers*, No. 1, August 2008.
27. S.I. Lia, C. Giuho and Z. Nazir, 'Sustainable Quality: From Space Stations to Everyday Contexts on Earth: Creating Sustainable work environments', *Proceedings of NES 2015, Nordic Ergonomics Society, 47TH Annual Conference*, 01 – 04 Dec 2015, Lillehammer, Norway, pp 1 – 8.
28. Elon Musk, 'Making Humans a Multi-Planetary species', *NewSpace*, Vol. 5, No. 2, 2017, pp 46 – 61.
29. S. Morad, H. Kalita, R.T. Nallapu and T. Jekan, 'Building small satellites to live through the Kessler Effect', [online] available: [arXiv.org/pdf/1909.01342.pdf](https://arxiv.org/pdf/1909.01342.pdf)
30. J. Banik, D. Chapman, S. Kiefer and P. Lacorte, 'International Space Station (ISS) Roll – Out Solar Array (ROSA) Spaceflights Experiment Mission and Results', *IEEE 7TH World Conference Photovoltaic Energy Conversion (WCPEC)*, 10 – 15 June 2018, Waikoloa Village, pp 3524 – 3529.
31. J. Hampson, 'The Future of Space Commercialization', *Niskanen Centre Research Paper*, Jan 25, 2017.

32. A.G. Davis, 'Space commercialization: The Need to immediately renegotiate treaties implicating international environmental law', Vol. 3, 2011 – 12, pp 363 -392.
33. R. Gatens, 'Commercializing Low – Earth Orbit and the role of the International Space Station', 2016, IEEE Aerospace Conference, 5 – 12 March 2016, Big Sky, MT, USA, pp 1 – 8.
34. T.M. Rutley, J.A. Robinson and W.H. Gerstenmeier, 'The International Space Station: Collaboration, Utilization and Commercialization', *Social Science Quarterly*, Vol.98, No. 4, Dec. 20167, pp 1160 – 1174.
35. M. Kganyago and P. Mhangara, 'The Role of African Emerging Space Agencies in Earth Observation Capacity Building for Facilitating the Implementation and Monitoring of the African Development Agenda: The Case of African Earth Observation Program', *International Journal of geo – information*, 2019, 8, 292, pp 1 – 22.
36. L. Shammas and T.B. Hohen, 'One giant leap for capitalist kind: Private enterprise in outer space', Palgrave Communications, Palgrave Macmillan, Dec. 2019, Vol. 5(1), pp 1 – 9.
37. F.A. Oluwafemi, A. Torre, E.M. Afolayan, B.M. Ajayi, B. Dhutal, J.G. Almanza, G. Potrivitu, J. Creach and A. Rivolta, 'Space Food and Nutrition in a long term manned mission', *Advances in Astronautics Science and Technology*, 2018, Vol. 1, pp 1 – 21.
38. E.L. Shkolink, 'On the verge of an astronomy cubesat revolution', *Nature Astronomy*, Vol. 2, May 2018, pp 374–378.
39. S. Gallozzi, M. Scardia and M. Maris, 'Concerns about ground based astronomical observations: A Step to safeguard the astronomical sky', arXiv, [online] arxiv.org/pdf/2001.10952.pdf, pp 1 – 16.
40. T. Beasley, 'NRAO – Statement on Starlink and Constellations of Communications Satellites', May 31, 2019, [online] available: public.nrao.edu/news/nrao-statements-commsats/
41. P. Seitzer, 'Mega – constellations and astronomy', IAA Debris Meeting, Washington, DC, 2019-10-19.
42. C. Adams, 'Will the data centres of the future be in space?' Parkplace Technologies.
43. J. Lai, Y. Zhang, L. Zhong, Y. Qu and R. Liu, 'Enabling Edge Computing Ability in Mobile Satellite Communication Networks', *IOP Conference Series: Materials, Science and Engineering*, Vol. 685, No. 1, 2019, pp 1–8.
44. B. Denby, and B. Lucia, 'Orbital Edge Computing: Machine Inference in space', *IEEE Computer Architecture Letters*, Vol. 18 June 2019, pp 59 – 62.
45. J. Straub, A. Mohammad, J. Berk and A.K. Nervold, 'Above the cloud computing: Applying cloud computing principles to create an orbital services model' *Proceedings SPIE*, 8739, Sensors and Systems for Space Applications, V1, 873909, May 21 2013.
46. Y.R. Fernandez, J.Y. Li, E.S. Howell and L.M. Woodney, 'Asteroids and Comets in Treatise in Geophysics', G. Schubert, T. Spohn (eds), Vol. 10, Chap 15, May 1 2015.
47. C.M.O.D. Alexander, K.D. McKeegan and K. Altwegg, 'Water Reservoirs in small planetary bodies: Meteorites, Asteroids and Comets', *Space Science Reviews*, 214(1), pp 1 – 63.
48. K.Molag, B.D.Winter, Z.Toorenburgh, B.G.Z Versteegh, W.V.Westrenen, K.D.Pau, E.Knecht, D.Borsten and B.H.Foing, 'Water – I Mission Concept: Water – Rich Asteroid Technological Extraction Research', 49th Lunar and Planetary Science Conference 2018 (LPI Contrib. No. 2083).
49. <https://www.asterank.com/>
50. N.Saeed, A.Elzanaty, H.Almorad, H.Dahrouj, T.Y.Al-Naffouri and M.S.Alouini, 'CubeSat Communications: Recent Advances and Future Challenges', *IEEE Communications Surveys & Tutorials* (Early Access) 27 April 2020, DOI: 10.1109/COMST.2020.2990499.