Building Smallsats from Consumer Electronics for Federated Earth Observation

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***Abstract*—We present an approach where a flexible, standards-based query language for spatio-temporal Earth data ("datacubes") is added to a nano satellite, allowing "any query, any time". This service runs on a dedicated compute board based on inexpensive consumer electronics. The expected benefit is to make Earth data exploitation easier to use, more flexible, and cheaper.**[1]

Keywords*— *satellite, edge processing, datacubes, federation, rasdaman

I. Introduction

With the advent of small satellites („smallsats") – also known as *nanosats* due to their small size – the wealth of Earth Observation (EO) data has exploded, paired by constantly increasing resolution (such as 0.2m) and frequent revisit times (such as several times per day). Typically, smallsats are based on a standard architecture relying on cubical basic building blocks of edge size 10cm, leading to the name *cubesat*. Common sizes include 1-unit, 3-unit, 6-unit.

As the output of such EO satellites is „Big Data", these frequently are „too big to transport". Transport is limited by the short time window of passing over a ground receiving station and the downlink bandwith; plans are to switch from radio to optical and laser communication to increase bandwidth, but this is not yet operational.

This situation consitutes a classical case for edge computing: „shift code to the server". While in the past computational capacities were insufficient, this is changing with modern hardware. Consequently, in-orbit processing of remote sensing imagery is receiving substantial attention recently [1][4], addressing both hyperspectral [21] and radar (SAR) data [7], and single-satellite as well as distributed on-board processing [22].

Nevertheless, this research field mostly transposes methods used on ground to edge devices, thereby retaining (and amplifying) known issues. Maybe most critical is that current Earth data exploitation requires a combination of very specific skills: remote sensing data wrangling: spectral bands and their use, cloud handling, radar data analysis, etc.; geo data specifics: coordinate reference systems, proper use of interpolation, vector/raster integration, etc.; programming: typically Python or R, knowledge about libraries and their use, parallel and distributed processing, file formats and their specifics and limitations, etc.; structure and organization of the archives used: EU Copernicus, NASA, national public archives, commercial archives, etc.; proper use of AI on Earth data: finding a suitable model or training one, bands collection, data preparation, patch generation, inference, statistically correct reassembly of patch results, etc. This complexity effectively limits exploitation to experts and excludes non-experts. As a consequence, exploitation is restricted and gets delayed, and experts are tied up in day-to-day business, effectively keeping them from other important tasks.

Specifically for satellite imagery, there are also severe technical limitations. The Verge observes [6] that less than 10% of the satellite data acquired arrive on ground. Reasons are manifold: transmission limits, in view of the ever-growing resolutions; processing limitations; incompatibilities; and more. Lt. Gen. Jack Shanahan / USAF is quoted with "Half of data acquired is not even looked at".

One answer to these challenges is to make satellite sensors intelligent enough to answer questions on data via edge computing. Expected benefits include better Quality of Service (insight instead of raw pixels) and higher availability of the satellite – as processed results typically are rather small compared to the raw imagery, more requests can be accommodated in a given timespan. If the access interfaces are sufficiently high-level, technical hurdles like the ones mentioned before get hidden „under the hood", thus enabling less skilled stakeholders to make use of the service. Some projects advocate running AI inference on board, and sometimes such models can even be updated in orbit.

However, we feel that focusing exclusively on AI is too limited. Instead of programming APIs, we suggest using query languages for submitting on-board jobs – similar to what SQL does on tables, but specialized to spatio-temporal geo datacubes. With suitable query languages, users do not need to program an algorithm and think in all detail about how to produce the result, but rather describe the result. Further, such languages allow „any query, anytime" without reconfiguration, possibly integrating AI inference, and consequently offer much higher flexibility and service quality. As it turns out, datacubes are not only more intuitive to humans but also lead to versatile, powerful service programming interfaces.

In a next step, such datacube-enabled edge devices can be federated for performing distributed processing and data fusion in orbit, ideally location-transparent for the user. Ultimately, such a federation will include data centers on ground, Earth observation satellites, and possibly more moving or fixed data sources (e.g., ocean sensors). Of course, thus increased capabilities and access through broader communities require advanced security, quota, and further protection mechanisms.

Hence, we propose a cloud/edge federation specialized

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on spatio-temporal datacubes, with special emphasis on asymmetric networks where compute power, storage, and networks latency covers a wide range, from edge devices up to large data centers.

In this paper we present the research plan and first results of project SkyFed [17] aiming at technology for standards-based edge services, location-transparently federated and relying on an inexpensive, yet powerful satellite architecture based on off-the-shelf consumer electronics.

II. In-Orbit Processing

Recently, in-orbit processing (as a special case of IoT edge processing) is increasingly gaining attention. On-board analysis of remote sensing imagery meanwhile has grown into a wide field [1][4], addressing aspects such as hyper-spectral image analysis [21] and radar (SAR) analysis [7], but also focused topics like ML support for determining the bands needed for given tasks [22].

In the past, special hardware was purpose-built to cope with the effects of ionizing radiation [15][18]. Such chips usually are both expensive and of limited power. Our hypothesis is that within the Low Earth Orbits (LEO) orbits of about 400 – 800 km, which is common for EO due to the high resolution achieved and the frequent revisits of different areas, the device will be sufficiently outside the van Allen belts with their high radiation intensity. Consequently, radiation damage is expected to be less of an issue, and the ESA OPS-SAT in-orbit experiment [5] has confirmed this.

A first in-orbit demonstration of datacube queries was performed in the ORBiDANSe project utilizing rasdaman [16]. On the 3-unit OPS-SAT, rasdaman was deployed, capturing Earth imagery and stacking it on board to a 3-D x/y/t datacube. Subsequently, queries were sent to the satellite which responded with the query results.

While OrBiDANSe convened all software into a single runtime system (with severe integration challenges), SkyFed makes use of separate board and processor, thus separating datacube processing from the processor operating the satellite. Consequently, development is decoupled, except from the necessary board integration with the on-board infrastructure (power supply, peripherals, etc.). Of course, this comes with some extra weight (about 20 grams) and power hunger (up to 5 Watts), which appears acceptable – in comparison, a recent 3-unit cubesat has a weight of up to 2 kg [14], hence the extra board adds 1% to the overall weight. We use the opportunity of board choice to go with a commercially available Raspberry Pi 5 running standard Ubuntu. This gives a convenient development environment, isolated from the remaining satellite, and with the same software infrastructure available as in common deployments on ground, thus allowing to keep a single code base for all deployments.

III. Datacube Edge Federations

Actionable datacubes have been pioneered with rasdaman [2][3], at the same time also coining the domain of Array Databases where n-D arrays form first-class citizens. Since some time now, the datacube concept has also been embraced by the geo data community. A deep analysis of 19 array technologies can be found in the Research Data Alliance (RDA) report [11].

Following a database approach, rasdaman offers a model-based geo datacube query language standard, *Web Coverage Processing Service* (WCPS) adopted simultaneously by ISO [19], OGC [13], and EU INSPIRE [20]. By way of example, the following query example extracts a “corridor” or “tunnel” from a 4-D x/y/z/t weather datacube to determine the absolute wind speed an aircraft will see when flying the route given by the polygon (note the 4-D time / altitude / Lat / Lon coordinates):

```
for $c in (wind)
return
  encode(
    clip(
      sqrt( pow( $c.u, 2.0 ) + pow( $c.v, 2.0 ) ),
      LineString(
        "2024-08-01T02:00" 5000 53.3899 -6.2183,
        "2024-08-01T03:00" 35990 51.5156 -0.1099,
        "2024-08-01T04:00" 35990 48.8647 2.3428,
        "2024-08-01T05:00" 35990 48.2137 6.3696
      )
    ),
    "json"
  )
```

Autonomous rasdaman deployments can be connected into a federation which for the users generates a single, homogenized information space. Queries arriving in the federation are automatically matched with data locations, and an optimized distributed execution plan is generated and executed. Thus, users do not need to care about data location. This is operational, e.g., in the EarthServer federation on 6+ Petabytes across USA, European and Asia. Goal is to extend this to include edge devices, for example, to combine satellites and data archives on ground into a single information space.

As the project does not have budget for launching the satellite built into orbit, and even less so a constellation, it was decided to build a demonstrator showing the idea of an Earth/Sky datacube federation. At the same time, this would serve as a vehicle for studying such highly asymmetric federations with widely differing compute power among the nodes and likewise differing transmission bandwidth.

Hence, a cluster of edge devices was built. Inside an acrylic case, eight towers of eight edge devices were assembled. Each unit consists of a Raspberry Pi 5. Each node is connected to the power supply through a USB-C cable. Communication is done through Wifi, both between the devices and with the outside world, consisting of (i) the federation mentioned below and (ii) connectivity to an external laptop acting as client. A separate service module, mounted on a wooden rack, holds the power supply, Wifi routers, and all wiring. On the software side, rasdaman was installed on top of Ubuntu 24.04 on each node, configured into a datacube federation incorporating all 64 devices [12].

IV. Smallsats Based on Consumer Electronics

To test SkyFed in orbit, a CubeSat mission is planned. CubeSats are standardized, small satellites with a scalable size architecture, enabling low-cost approaches thanks to standardized parts and interfaces.

In the space industry, the process of adapting the latest technologies is slower than in other industry branches. A key factor is the extreme environment of space which imposes hurdles for the adaptation of e.g., modern electronics.

Over the past decade, however, a shift in space industry can be observed. Launch costs have decreased, opening door for innovative ideas and concepts with shorter turnaround. Missions such as ArduSat [9] have already successfully demonstrated the general usability of commercial components in space, especially in Low Earth Orbit where radiation levels are lower and temperature ranges less extreme. Cheaper spacecraft allow the launch of larger numbers of satellites, which is specifically relevant for satellite *constellations* (*swarms*). This way, the reliability of a space mission overall does no longer rely on the reliability of an individual spacecraft; rather, the constellation can dynamically redistribute roles for more resilience.

Hence, new edge technologies offer the potential for lightweight and cheap spacecraft, yet powerful enough to handle complex processing. Research such as VIBES [8] aims at utilizing consumer electronics for space flight applications despite the challenges [10]. A SkyFed spacecraft could be based on the VIBES Pioneer 3U CubeSat (Fig. 2).

Fig. 1. Raspberry cluster (left) with service module (right)

Fig. 2. VIBES nanosat vision (source: HSB)

V. Conclusion and Future Work

We presented a novel approach to enhancing service quality of Earth observation satellites based on a distributed, AI-enabled database architecture allowing spatio-temporal on-board analytics by sending up datacube queries. Cloud / edge federation establishes a single common data space for users based on open standards, seamlessly combining data centers and satellite swarms. The low power consumption in combination with off-the-shelf consumer electronics components reduces the cost footprint.

Next steps include coupling rasdaman and its Raspberry board using a Raspberry Pi Compute Module 5 to representative peripherals, including a multi-spectral camera, GPS sensor, and telemetry downlink.

The existing query optimizations in rasdaman need to be extended to cope with the highly asymmetric cloud/edge node capabilities for generating efficient distributed query plans. In parallel, the consortium is seeking for a rideshare opportunity to assess the cloud/edge federation in orbit.

Altogether, SkyFed aims at (i) democratizing Earth data access to communities beyond remote sensing programming specialists and (ii) significantly reducing the satellite costs.

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