WHO_2CARES - Mission Proposal

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1 Background

The WHO_2CARES satellite cluster will monitor the Earth's surface and troposphere at a higher spectral and temporal resolution of any satellite system of its kind. Its primary foci are across various useful earth science observations: clouds, aerosols, surface reflectance, and the oxygen A-band. Each of these retrievals is discussed in more detail below. These measurements are particularly valued for ongoing studies of anthropogenic climate change.

1.1 Existing Technologies

Current state-of-the-art Earth Observing (EO) satellites and sensors offer some view into cloud, aerosol, albedo, and land use. This is done, in part, using the visible and near infrared (NIR) parts of the electromagnetic spectrum. The WHO_2CARES satellite cluster will refine and miniaturize these technologies, bringing them to the cutting edge of nanosatellite design. WHO_2CARES will offer fast temporal resolution, regional scale spatial resolution, and hyperspectral sensors to monitor fast-moving and diverse environments on our Earth's surface and in the troposphere. WHO_2CARES also gives a completely new design facet of 3-dimensional data builds, with satellite looking pairs in the cluster offering 3D geometric resolution of surface features and cloud tops.

At first, it is pertinent to explore the existing state-of-the-art to discover how the visible-NIR has been observed in the past and how we can effectively build upon this great wealth of satellite EO data.

1.1.1 Hyperion (earth Observing-1)

Hyperion was a hyperspectral, high-resolution imaging instrument aboard the experiment Earth Observing-1 (EO-1) satellite. Originally launched in 2000, it was expected to have a lifetime of 1 year but it far extended this, reaching a total life time of 17 years. EO-1 was deactivated in 2017. It had 220 unique channels with a spectral bandwidth of just 10 nm, across a spectral range of 0.4 – 2.5 µm. Despite a primary mission of validating the instruments aboard, EO-1 provided some land imagery that was coupled with LandSat 7 to validate quality. Another great achievement of Hyperion was a ground resolution of 30m, allowing less-than regional scale observations to be made. These highly advanced spectral and spatial resolutions came at the cost of temporal resolution, with a total of 16 days return time (centre for remote imaging and processing, 2018).

1.1.2 MISR

Multi-angle Imaging SpectroRadiometer (MISR) can distinguish the volume and types of atmospheric aerosols particles, the types and height of clouds, and the distribution of land surface cover (Diner et al., 1998). MISR offers nine viewing angles to resolve geometric variations across observed scenes. MISR also operates in 4 different channels; red, green, blue, and near-infrared. MISR is a specialist instrument for cloud top height and pressure retrievals, cloud albedo, aerosol characterization and mapping, and land surface albedo and classification. These technologies are now validated and can be adapted across WHO_2CARES system. WHO_2CARES offers a higher spectral and temporal resolution thus offering features like a more precise pressure-temperature profile and the ability to model within the diurnal cycle.

1.1.3 MODIS

Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument operating on the Terra and Aqua NASA spacecraft, first flown in 1999 and again in 2002 (Justice et al., 1998). It offers a view of the atmosphere, land, and ocean measuring across the visible and infrared spectrum. Although not offering the stereoscopic properties of MISR (above), it has a high spectral, spatial, and temporal resolution. MODIS is key player in the current studies of global cloud cover and cloud height. It also offers land use products such as vegetation indices, burned area products, and ocean colour features. The ability to not only provide moderate to high resolution products, but also offer so many products to the end user, displays the power of MODIS. To provide a higher temporal and spectral resolution, as well as a stereoscopic ability, across the same suite of WHO_2CARES products to the scientific community would be advantageous to all earth scientists with an interest in remote sensing.

1.1.4 VIIRS

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a sensor aboard the Suomi NPP Weather satellite. On portion of its collected data are used as environmental data records for the NOAA National Weather Service, whilst the other portion stream through NASA and offer earth system data to the wider community (Justice et al., 2013). The primary aim of VIIRS is to provide complimentary cloud data to MODIS and other NASA instrumentation across sunlit conditions in 12 bands, and an additional 9 infrared for surveying both night and day clouds. It also offers smoke and fire detection and atmospheric aerosol characterization and mapping (Hutchison and Cracknell, 2016). It offers slightly better spatial and temporal resolution than MODIS, but at the cost of its spectral resolution. WHO_2CARES will be building on this technology to provide measurements on shorter timescales, although they WHO_2CARES products will not be available in the mid- to long-wave infrared.

1.1.5 TROPOMI

The TROPOspheric Monitoring Instrument (TROPOMI) is primarily an atmospheric chemistry instrument aboard the Sentinel-5p ESA satellite launched in 2017. Alongside chemical species, it also monitors cloud fraction, albedo, and top heights, and aerosol layer height (Institute, 2017). TROPOMI data processing can compute these using returns from the oxygen A-band, with a very high spectral resolution. The $<$1nm spectral resolution comes at a loss of spatial resolution, which is 3.5 – 7 km at nadir. The oxygen A-band will also be measured in WHO_2CARES to give information on clouds and aerosols, offering a much improved spatial and temporal resolution than TROPOMI.

1.1.6 Flock (from Planet Lab Inc.)

The Flock is a nanosatellite cluster (and the only nanosatellites to be discussed in this background) operated by private company Planet Labs Inc. The Flock instruments are all loaded aboard a 'Dove, a 3U CubeSat, a nanosatellite standard of 10x10x30 cm. The satellite constellation currently consists of ~120 satellites, some of which were utilised as mechanical and engineering tests, but with most capturing 4 band imagery of earth's surface. It is believed that a 3hr temporal resolution can be achieved with a nanosatellite cluster of ~92 CubeSats. Despite a significantly reducing spectral capture to a 3-band RGB camera with one NIR component, the Doves can give a spatial resolution of 3 to 5 m. This resolution is useful for a community interested in small-scale local changes, especially in land use or urbanisation.

However, WHO_2CARES wishes to give the scientific community a regional scale data set to monitor changes on kilometre wide scales. By reducing the spatial resolution, the spectral resolution can be improved with some hyperspectrality brought in across the Vis-NIR wavelengths of interest. The high quality temporal resolution that can only be given by such a dense network of nanosatellites is of particular important when considering the state-of-art contribution offered by Planet Lab Inc.'s designs.

1.2 Cloud Observations

Accurate information on cloud properties, types, and their spatial and temporal variation along the atmosphere is crucial for climate studies and models. Cloud representations vary among global climate models, and small changes in cloud cover have a large impact on the climate. Differences in planetary boundary layer cloud modeling schemes can lead to large differences in derived values of climate sensitivity. A model that decreases boundary layer clouds in response to global warming has a climate sensitivity twice that of a model that does not include this feedback.

Table 1: Summary of relevant satellite missions

Satellite/ Instrument	Temporal Resolution	Spatial Resolution (km)	Spectral Range (μm)	Spectral Bands or Hyperspectral Resolution	Currently Active?
Hyperion	16 days	0.3	0.4 – 2.5	Hyperspectral 10 nm	No
MISR	9 days	0.28 - 1	0.45 – 0.87	21.9 – 41.9 nm	Yes
MODIS	1 – 2 days	0.25 - 1	0.4 – 14.4	36 spectral bands	Yes
VIIRS	1 day	0.38 – 0.75	0.41 – 12.5	21 spectral bands	Yes
TROPOMI	1 day	3.5 - 7	0.27 – 0.78 with an extra 2.3-2.39 in IR	0.25 – 0.54 nm	Yes (fully online later 2018)
Planet Labs	3 hrs	0.03 – 0.05	0.45 – 0.86	Up to 4 spectral bands	In Progress
WHO$_2$CARES	3 hrs	1	0.4 – 2	Hyperspectral 2 nm - 10 nm	

Also, not all clouds are the same, different types of clouds affect the Earth's climate differently. Some types of clouds help to warm the Earth; others help to cool it. The radiative effects of clouds depend strongly on cloud properties such as thermodynamic phase, optical thickness and droplet effective radius. The IPCC reported in 2007 that it projects the Earth's average temperature to be about 1.8 to 4 degrees Celsius higher by the end of the century than it was in 1990 – a rapid rate of increase compared to observed rates of increase in the Earth's recent history.

Scientists could probably narrow down the Earth's projected temperature range further if they better understood the relationships between clouds and climate as well as other factors, such as the amount of greenhouse gases that will be pumped into the atmosphere by 2100. Most scientists doubt that the net cooling effect of clouds will ever be large enough to completely offset ongoing warming. However, many scientists (Marshak and Davis, 2005) say that if warming were to increase the number of kind of cooling clouds or decrease the presence of warming clouds, the current net cooling effect of clouds on the Earth's climate would probably increase, and thereby moderate, or offset, ongoing warming, and the Earth's-end-of-the-century temperature may be pulled down toward the lower end of its predicted range.

On the other hand, the opposite effect could happen and the upper end of the predicted range is also possible and the increasing of the warming cycle would be perpetuated.

The reason why clouds impact climate differently resides in their heights and thickness. On the one hand, stratus clouds hang low in the sky – usually within two kilometers of the Earth's surface—and resemble a gray blanket covering thousands of kilometers of sky. Because these clouds block sunlight from reaching the Earth, they act like a sun-screen or shady umbrella that helps cool the Earth. Therefore, they have a net cooling effect that helps offset warming.

Secondly, cirrus clouds are wispy and feathery, and positioned up to 20 kilometers above the Earth's surface. Cirrus clouds let much sunlight pass through them and may also trap the Earth's heat, just as greenhouse gases do. Therefore, they have a net warming effect that helps magnify warming.

Finally, Cumulus clouds, they extend vertically high in the sky. They have sharply defined edges, may form alone, in lines or in clusters. Cumulus clouds can block sunlight, but also trap the Earth's heat. Their net effect on warming depends on their heights and thicknesses.

Also, global warming is expected to change the distribution and type of clouds. It is found that clouds are moving away from the equator as temperatures rise. Subtropical dry zones have also been expanding. Observed and simulated cloud change patterns are consistent with poleward retreat of mid-latitude storm tracks, expansion of subtropical dry zones, and increasing height of the highest cloud tops at all latitudes (Witze, 2016). These results indicate that the cloud changes most consistently predicted by global climate models are currently occurring in nature. Clouds heights do, however, vary considerably from year to year in connection with weather and climate phenomena. La Niña and El Niño events have the strongest effect, with the 2008 La Niña lowering global clouds on average by 40 meters and El Niño events pushing the upward (Lelli et al., 2014). Beyond that, the researchers found differences in Southern Hemisphere and Northern Hemisphere cloud behavior and regional correlations that warrant further investigation. With cloud heights naturally varying so much, it is thought (Rasmussen, 2017) that it could take at least 15 years of data to spot any possible global effects of climate change. "All we can say at the moment is that the global trends in cloud heights, if they are there, are being swamped by El Niño – La Niña fluctuations", "It will take a lot longer till we can tease out these long-term trends.". In terms of clouds, many efforts have been dedicated to the retrieval of their properties and distribution along the atmosphere. Passive satellite imagers are the most widely used instruments for cloud retrievals as they provide long-term, global coverage at acceptable cost for the user. The Advanced Very High Resolution Radiometer (AVHRR), on board the NOAA satellites since the end of the 1970s, has been a significant contributor to many global cloud climatologies. AVHRR with its four to six spectral channels allows the retrieval of key cloud properties by abutting pixels that assemble a seamless image. The heirs of the AVHRR were launched in several NASA/ESA research missions, on board satellites such as Terra, Aqua, the European Remote Sensing Satellite (ERS-1/2) and the Environmental Satellite (Envisat). Those are the Moderate Resolution imaging Spectroradiometer (MODIS), the Along-Track Scanning Radiometers (ATSR-1/2) and the Advanced Along-Track Scanning Radiometer (AATSR), which provide an increased number of spectral channels as well as higher spatial resolution (1 km footprint size) than AVHRR. The MODIS and ATSR/AATSR sensors include the spectral channels of AVHRR but have additional ones in the visible, near-infrared and, in the case of MODIS, also in the thermal infrared. In addition, they have an increased spatial resolution as well as contribution to increasing the observation frequency. The datasets derived from these measurement retrievals are useful for climate studies and cover more than one decade. ATSR provides its Global Retrieval of ATSR Cloud Parameters and Evaluation (GRAPE; Sayer et al., 2011) for ATSR/AATSR, MODIS (NASA) its Collection 5 (Platnick et al., 2015, 2017; Marchant et al., 2016). These cloud properties datasets have now reached quality levels that facilitate qualitative and quantitative assessments of clouds in the Earth's climate system, even availability to understand cloud processes and the evaluation of atmospheric models. Till now, with visible and Near Infrarred bands cloud products such

Cloud Optical Thickness, Effective Radius, Liquid Water Content and Cloud Albedo can be derived. There also have been some efforts devoted to obtain cloud heights and cloud thickness through the analysis of the O2-A-Band changes by means of sensors like SCIAMACHY/GOME/GOME-2. Given the high degree of measurement accuracy afforded by current instruments, the reliability of derived atmospheric products no longer depends as heavily on instrument calibration and noise but more so on the choice of spectral bands, the forward model, and the method of inversion. In addition there is still potential to improve the current datasets. WHO_2CARES mission will offer a hyperspectrality, temporal resolution and 3-Dimensional analysis of clouds that has not ever seen before. With its higher spatial and temporal resolution products such as cloud optical thickness can gain accuracy, and coupled with cloud heights retrieval through hyper spectral analysis may help to derive new and improved cloud types products. This could lead to finally determine the current trend of cloud heights and movement due to global warming and climate change.

1.3 Surface Observations

MODIS has brought unprecedented data to scientists making high quality, global datasets available to land, ocean and cryosphere applications. WHO_2CARES aims to continue this legacy by observing the earth in the visible and near infrared region in which the MODIS land and ocean channels are located. Instead of 20 channels in this region, however, WHO_2CARES will provide hyperspectral information with more than 100 channels. This will open the door to a range of novel science applications, building upon and extending the MODIS range of surface products.

1.3.1 Land

Synoptic and repetitive observations of vegetation cover and land use are of great importance for the modeling and prediction of climate change as well as the planning of urban and industrial development.

1. Vegetation

   Besides regulating the regional carbon and hydrologic cycle, vegetation cover has an important impact on atmsopheric composition and climate feedbacks. The study of these processes require fine scale characterization of the ecosystems involved. By providing high spectral resolution at moderate spatial resolution, WHO_2CARES aims to close an important gap in the global monitoring system of vegetation. Numerous studies have highlighted the potential of and need for spaceborne hyperspectral observations. An example is the work by Haboudane et al. (2004) who developed robust, hyperspectral vegetation indices and showed that they outperform the normalized difference vegetation index in the prediction of green leaf area index (LAI). Furthermore, airborne hyperspectral observations are commonly used for vegetation type classification. Relevant applications of such informations can be found in the works of He et al. (2017) who study the expansion of evergreens in the Siberian forest or Winkler et al. (2017) who identify droughts affecting the agriculture in Africa.

2. Landuse and Disaster Response

   The revisiting inverval of three hours that will be achieved by WHO_2CARES will further increase the frequency at which a given location is observed. Clearly, the additional spectral information content of WHO_2CARES data will allow a more detailed mapping of land use and land cover. Moreover, the improved spatial resolution will be of great value for disaster response. As an example, data from the MODIS instruments has been used to coordinate the response in the wake of superstorm sandy. The biggest challenge with MODIS data is cloud cover that obstructs the view on affected areas. Since WHO_2CARES will see the same location twice as often as MODIS does, this will greatly improve the probability to obtain useful live data for disaster response.

1.3.2 Cryosphere

Observation in the visible and near infrared are commonly used to study regional and global snow and ice cover. Applications are spatiotemporal snow cover variability (Dariane et al., 2017; Ga et al., 2017) and their impact on regional climate and hydrology. Also for observations of the cryosphere, the additional spectral information provided by WHO_2CARES will help to improve our understanding and modeling of relevant processes. Dozier and Painter show that hyperspectral observations of snow cover can be used to determine both snow cover and snow albedo, which are important inputs for cryosphere models.

1.3.3 Ocean

With regards to the ocean, the additional spectral information delivered by WHO_2CARES will allow to further extend on the MODIS product and application range. WHO_2CARES has the ability to bridge the gap between MODIS data and data from the HICO sensor for monitoring of the coastal ocean. The HICO sensor was an experimental sensor that was operational from 2009 to 2014 and flown onboard the ISS, and delivered hyperspectral observations in the range from 380 to 960 nm. Keith et al. (2014) show how the hyperspectral data provided by HICO can be used to observe changes in coastal and estuarine water quality.

1.4 Aerosols

2 Research Tools

2.1 Orbit

Type of orbit: In order to retrieve a global coverage a satellite should be launched in a near polar orbit. In such an orbit, the angle of the satellite orbit to the equator is roughly 90 degrees. To ensure a consistency in the retrieved data through time, it is also interesting to have a constant local time of the satellite revisit. This requirement is met in sun-synchronous orbits (constant angle between orbital plan and sun direction). These orbits are often low in altitudes (< 1000Km). A low earth orbit also presents the advantages of a rapid rotation periods (around 90 minutes) and a lower launch cost. A swarm of nanosatellites As written before, among other advantages, nanosatellites deployment costs are relatively low compared to other classic satellites missions. These lower costs will enable us to launch tens of nanosatellites. A well-built swarm or clusters of satellites will thus overcome the time resolution problem that other satellites missions are encountering.

2.2 Communications

Communication infrastructure is one of the most critical components of satellite system design. In most cases, the scientific return of a task is directly affected by the capacities of the communications subsystem. These constraints are particularly evident on resource-constrained small satellites, such as "CubeSats" (Kingsbury and Cahoy, 2015).

Traditionally, Low Earth Orbit Nano-satellites use radio frequencies (RF) for communication purpose at VHF, UHF and S-band. These traditional methods provide data rates up to 256 Kbyte/s (Ochoa et al., 2015). In this study, 1 TB of data transmission per day is required and with traditional methods, it is not possible to transmit data at this level. Because of this, it has been decided to use optical communication systems for this study.

Optical communication systems use lasers to encode and transmit data with higher speed and density than RF-based communications. Smaller antennas, lower power requirements, and increased spectrum availability enable optical communications to be integrated into CubeSats more easily than radios, enabling affordable communications solutions for Nano satellites missions (NASA, 2017).

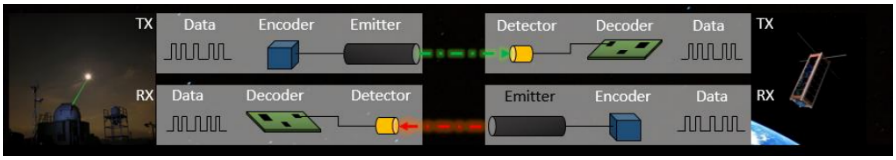

Figure 1: Two-way CubeSat based optical communications setup. The transmitter (TX) and the receiver (RX) (NASA, 2017)

In helio-synchroneous, one complete orbit taking 90 minutes. Our satellites orbit the Earth 16 times per day, the cubesat will transmit data to the ground station. The time window will be 7.5 minutes before the satellite is below horizon. Within this 7.5 minutes the satellite and the ground station need to establish a data link and transfer the data. With optical communication we can transmit 25 MB/s data. The equation below is used to calculate the required ground based station number to transfer 1 TB/day for a satellite;

“Unlike radio communications, optical communications are interrupted by clouds. Therefore, any high availability laser communications system must include a strategy for ensuring a cloud-free line of sight (CFLOS)” (Link et al., 2005).

Even the most cloud-free locations are cloudy about 30\achieving system availabilities higher than 70\strategy. The most effective strategy is “site diversity”, which is having redundant sites so that if one is clouded out another can be used as a backup (Link et al., 2005).

To minimize the effect of clouds, number of required ground based station will be doubled. In addition to this, 1 TB of non-volatile storage on SD cards will be replaced on satellites.

2.3 Onboard Instruments

One of the main advantages of the Earth observation using nano satellites technique is a possibility of launching a fleet of satellites with similar onboard instruments. To achieve global coverage of the Earth surface every 3 hours during WHO_2CARES mission a fleet of 90 nanosatellites is needed. Two spectrometers (for UV-VIS and IR spectral ranges) will be installed on each of them. Field of view of the instrument is 40° (~400x400 km on the surface of the Earth) with spatial resolution 0.2 km. For clouds 3D structure reconstruction, it is necessary to observe atmosphere in nadir from two different points on the orbit. We suggest a scheme of satellites motion when all parts of the fleet move in pairs with a constant distance between partners – d=200 km. In this case fields of view of two detectors in pair overlap (~200x400 km) and provide continuous observation of the underlying part of the atmosphere from two orbital points (Fig. 1). The optical measurement principle is depicted in Fig. 2. The idea is to use to detector in order to cover the spectral range from 165 nm to 1800 nm. The first detector will be a standard 2048 x 2048 pixels wide CCD or CMOS in order to cover the UV-VIS spectral range (165 nm - 1100 nm) and a 2048 x 2048 pixels CMOS-like IR-array (surely made from HgCdTe or InGaAs) to cover the NIR spectral range (800 nm – 1800 nm). The hyperspectrality will be ensured by using a Fabry-Pérot Fourier transform spectrometry technique to retrieve the spectral component [1,2]. This will allow to attain the wanted spectral resolution as well as the hyperspectrality by changing the Fabry-Pérot resonances and hence sweeping across the bandwidth. Furthermore, the Fabry-Perot interferometer can be much lighter and more compact than a conventional interferometer configuration such as Sagnac or Michelson interferometry designs and hence are suitable for remote sensing applications [2].

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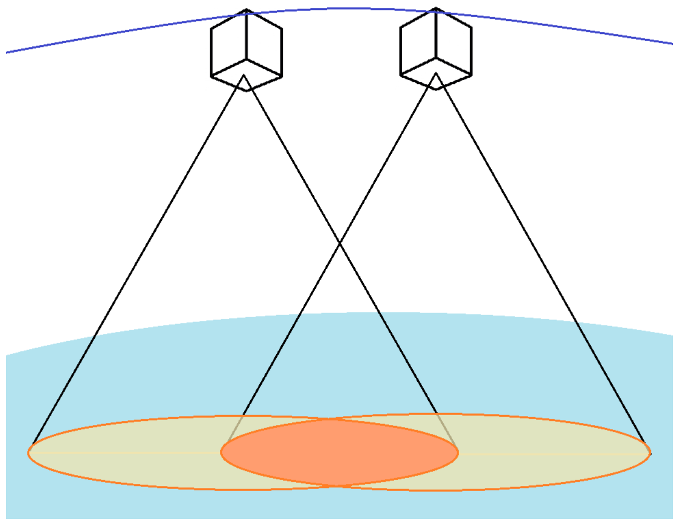

Figure 2: Overlapping of the field of views of two detectors in pair.

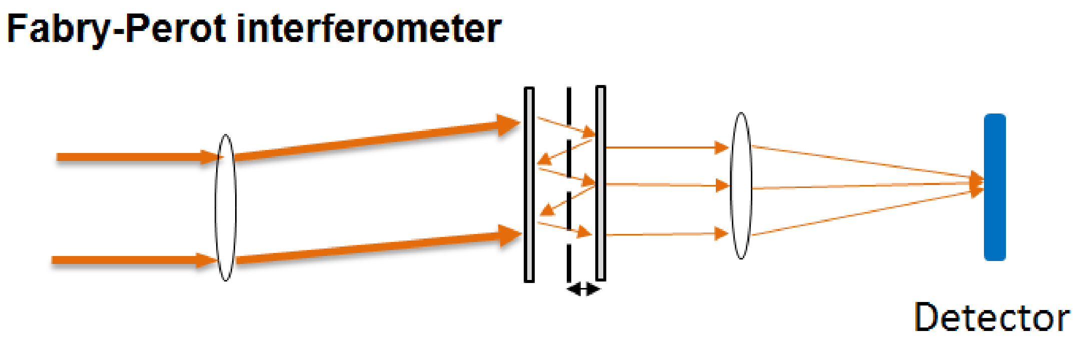

Figure 3: Overlapping of the field of views of two detectors in pair.

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