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Sensor Webs of Agile, Small Satellite Constellations and Unmanned Aerial Vehicles with Satellite-to-Air Communication Links

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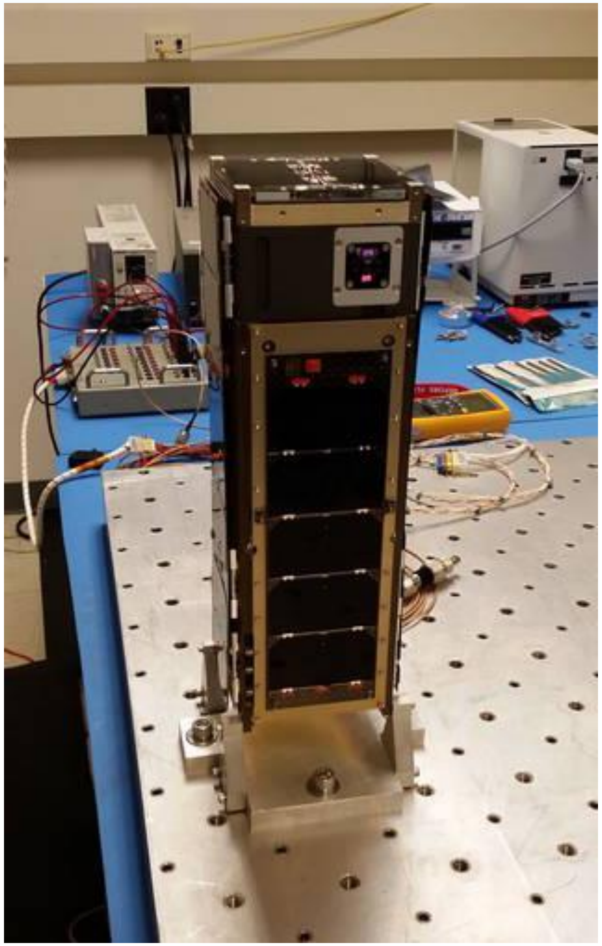
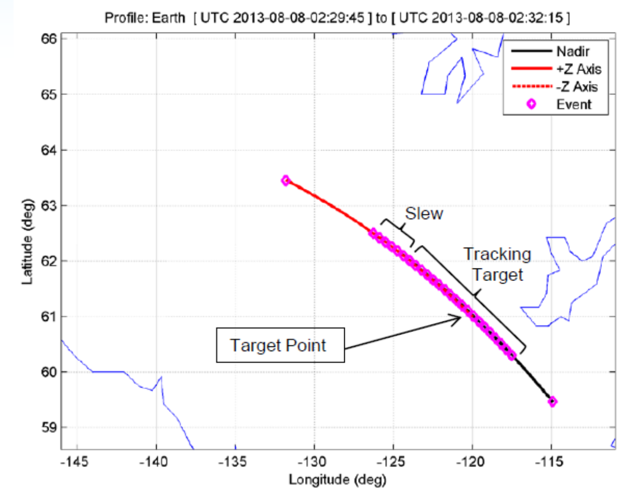
A Decade of EO CubeSats

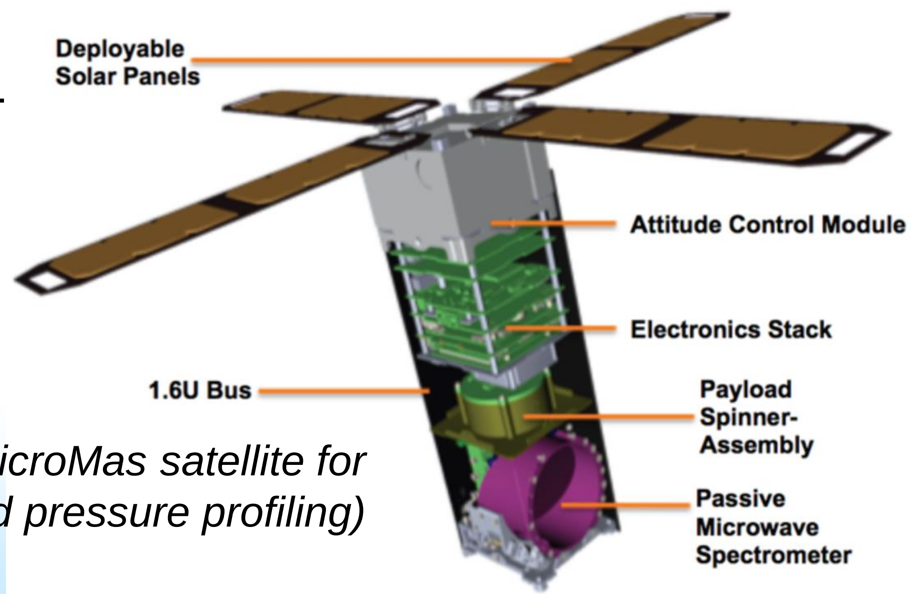


IceCube ready for ISS – radiometer to study ice clouds (NASA GSFC)

- In 1999, Cal Poly and Stanford University developed the CubeSat specifications to promote and develop the skills necessary for the design, manufacture, and testing of small satellites intended for low Earth orbit (LEO)
- Since 2007, science based satellites
- Science selected by C3PO constraints



AeroCube Fire Detection (CubeSat Developers' Workshop, April 2014)



3U Cubesat (MicroMas satellite for temperature and pressure profiling)

Why did Small Sats get popular?

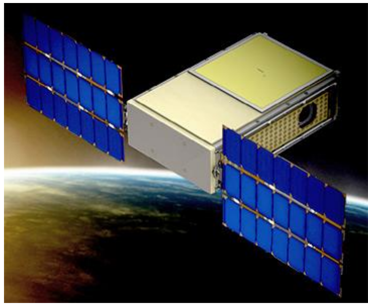
- The advent of the CubeSat standard
- Miniaturization of propulsion, power systems or electronics
- Frequent and cheaper launch opportunities by emerging companies such as SpaceX and RocketDyne
- Hosted payload opportunities on traditional rockets using the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)
- Deployment mechanisms for CubeSat payloads using the PPOD launcher or NanoRacks
- Increasing availability of ground stations

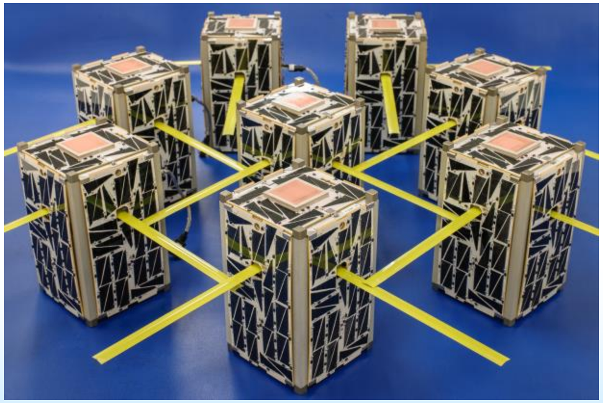
Deployment and operation of large numbers of small satellites more feasible than it ever used to be

CubeSats/NanoSats at NASA Ames

SPHERES

Proposed and funded BioSentinel





Edison 1.5U satellites

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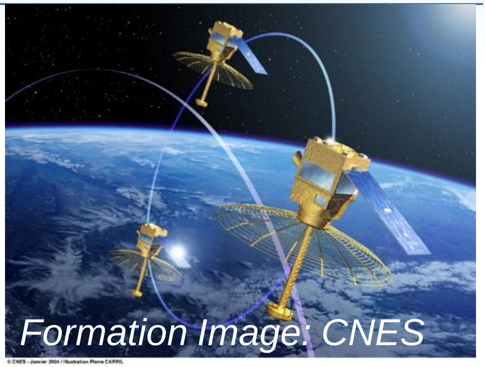
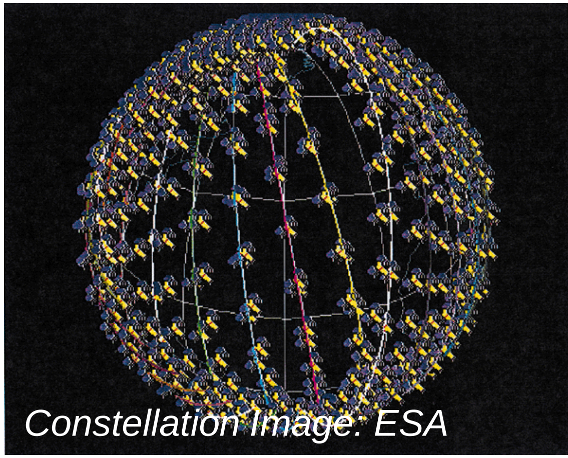
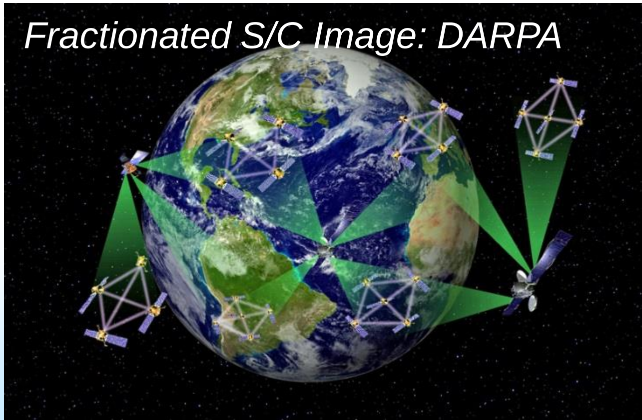
Why Multiple Satellites?

- **Distributed Space Missions (DSMs):** Constellations, formations, ad-hoc constellation - home or hetero, cellularized systems, federated satellites
- **Performance**: Improve sampling and range in spatial (synthetic apertures), temporal (constellations), spectral (fractionated S/C), angular (formations) dimensions
- **Cost**: Need more inter-operability planning, autonomy, scheduling commands + data, ground station networks
- **Ilities in Operations**: Flexibility, Reconfigurability, Scalability, etc.
- **Better Design**: Many conflicting variables and objectives thus better methods needed in Phase A+ - coupled models, machine learning, planning/scheduling methods, etc.


Formation Image: CNES

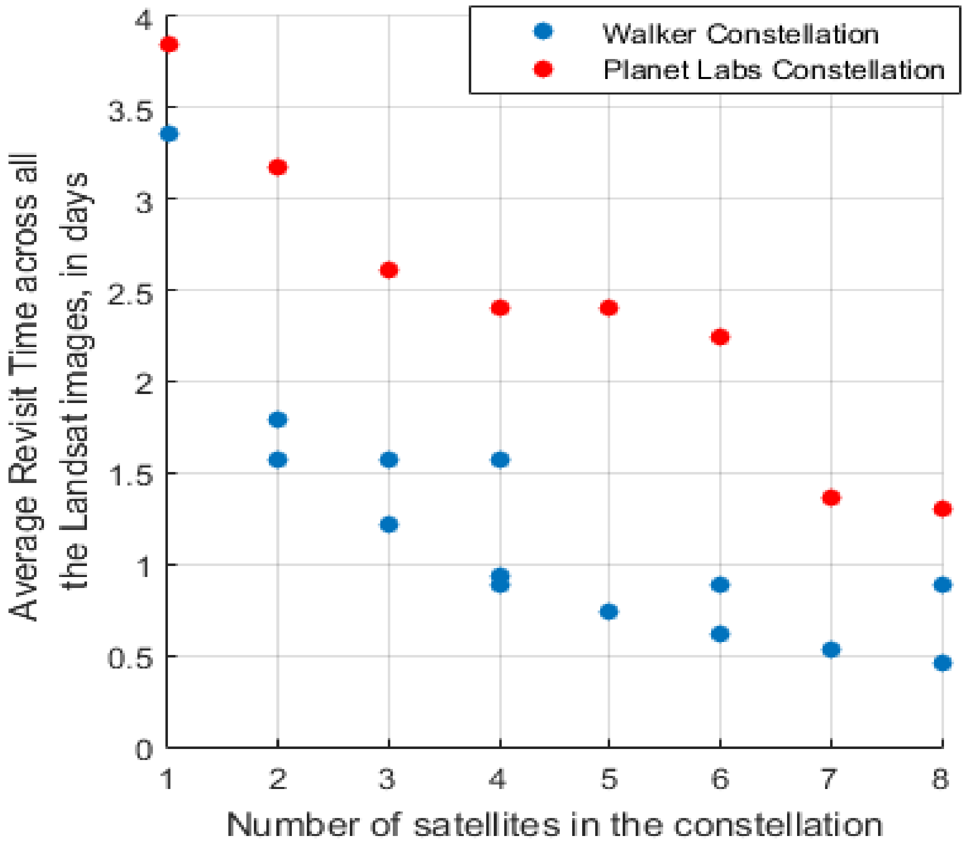

Constellation Image: ESA

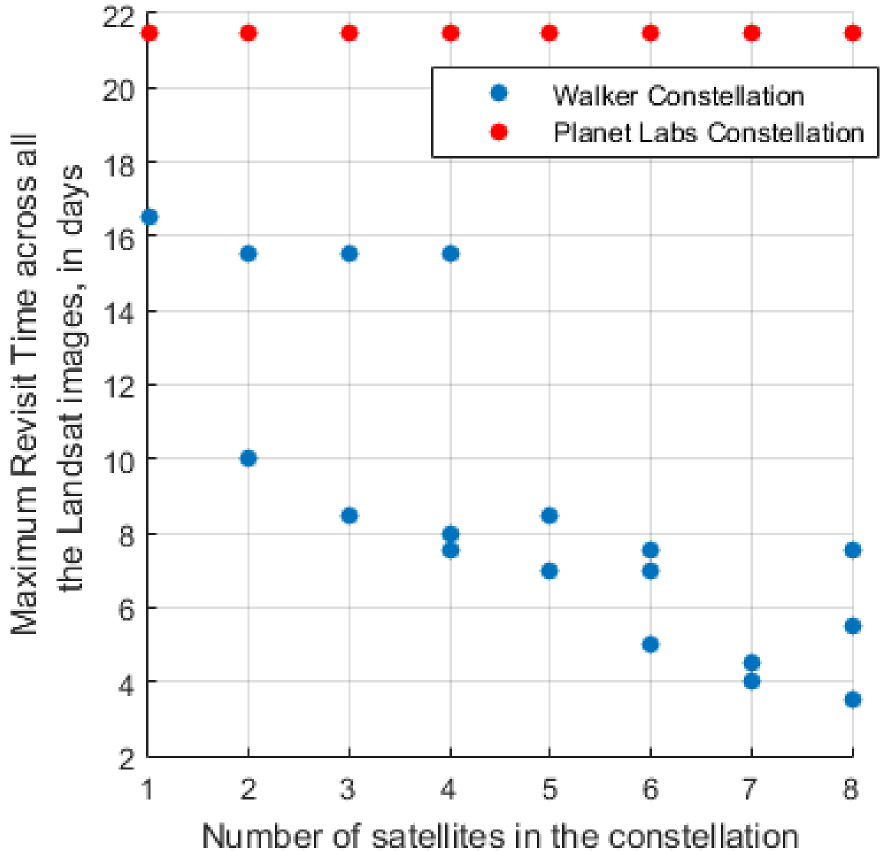

Fractionated S/C Image: DARPA

EO Constellation Coverage

NASA's Tradespace Analysis Tool for Constellations:

Landsat w/ 1-8 sats => 20 uniform Walker and 8 Ad-Hoc constellations
Area of Interest: USGS Landsat grid of 17000 land/coastal images.
TAT-C takes **<15 hours** of run-time compared to STK's **12 days**.



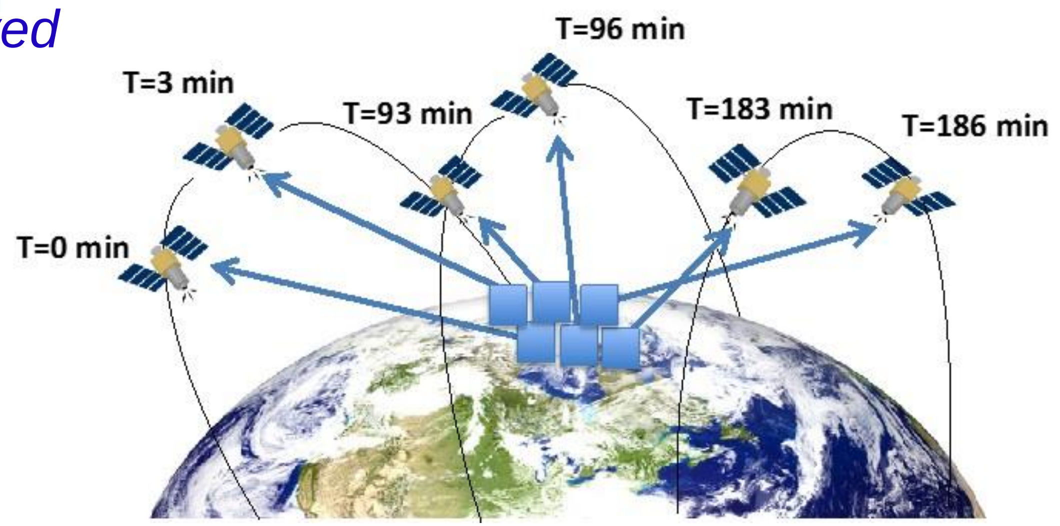


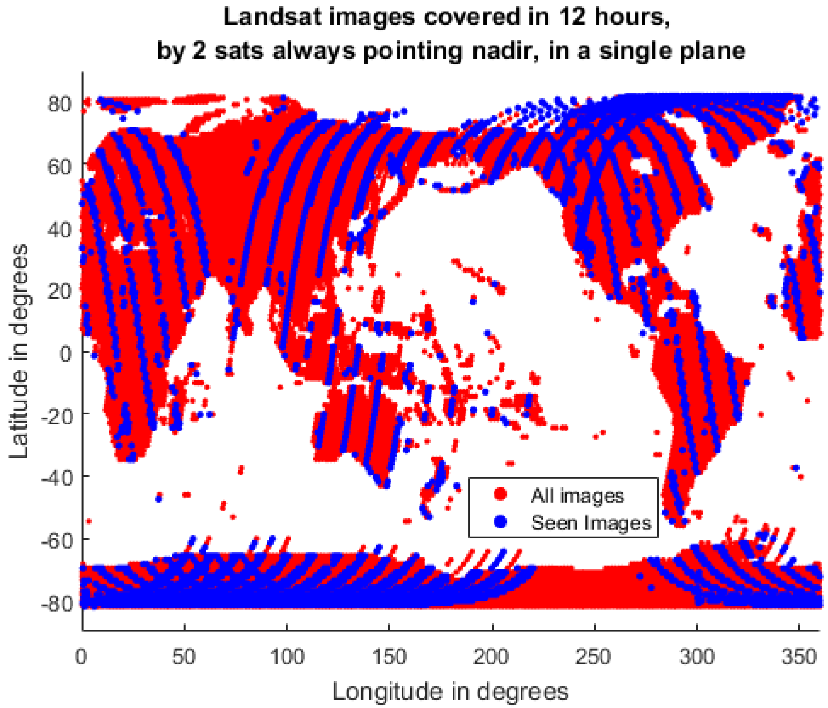
Reference: S. Nag, S.P. Hughes, J.J. Le Moigne, "Streamlining the Design Tradespace for Earth Imaging Constellations", AIAA Space Conference, Long Beach California, September 2016

Constellation Design w/ Pointing

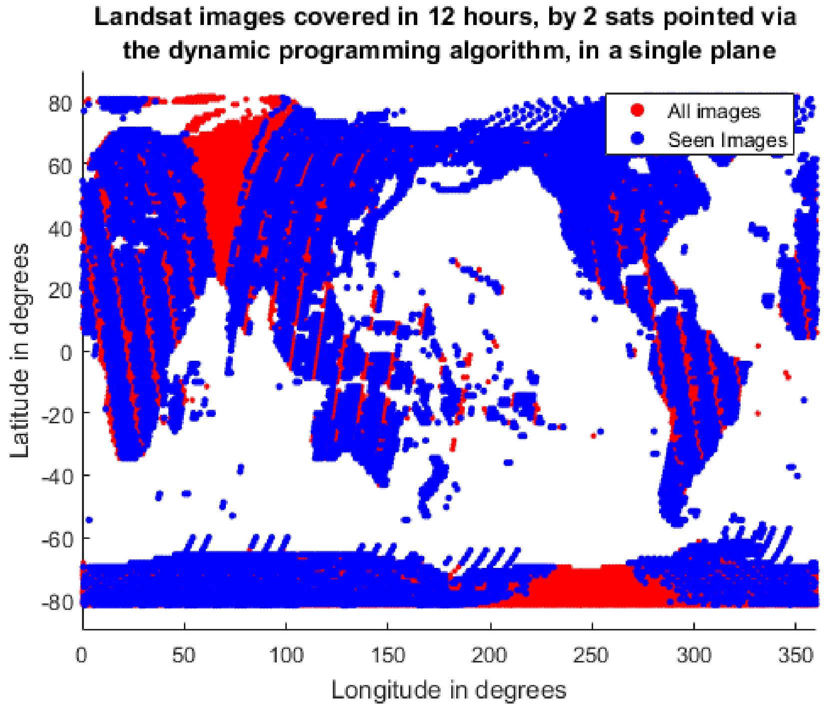
All Coverage products are improved by Constellations

Scheduling pointing ops for narrow sensors on LEO sats to maximize global coverage + minimize image distortion under attitude control, cloud cover, etc. constraints.





vs.



Autonomous Planning and Scheduling

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Cubesat onboard processing capability has grown by Moore's Law

- Space Cube Mini (commercial Xilinx V5 or radiation hardened Space-grade Virtex-5QV) can process SAR images and compress more than 6x
- NASA GSFC's Core Flight Software (used on LADEE, LRO, GPM, MMS among others) has been demonstrated on the Raspberry Pi 3
- Open source languages such as PLEXIL and government access software such as CASPER (EO-1) are being used for autonomous scheduling on ISS, rovers
- Images can be processed and next observations automatically scheduled on satellites

Figure 6: Photo of the SpaceCube 2.0 Mini CubeSat processor (image credit: NASA)

Reference:
https://cfs.gsfc.nasa.gov/

https://directory.eoportal.org/web/eoportal/satellite-missions/i/ipex

http://plexil.sourceforge.net/wiki/index.php/Main_Page

http://casper.jpl.nasa.gov/

UAV Comm and Surveillance

Unmanned Aircraft System (UAS) Traffic Management (UTM)

Enabling Civilian Low-Altitude Airspace and Unmanned Aircraft System Operations

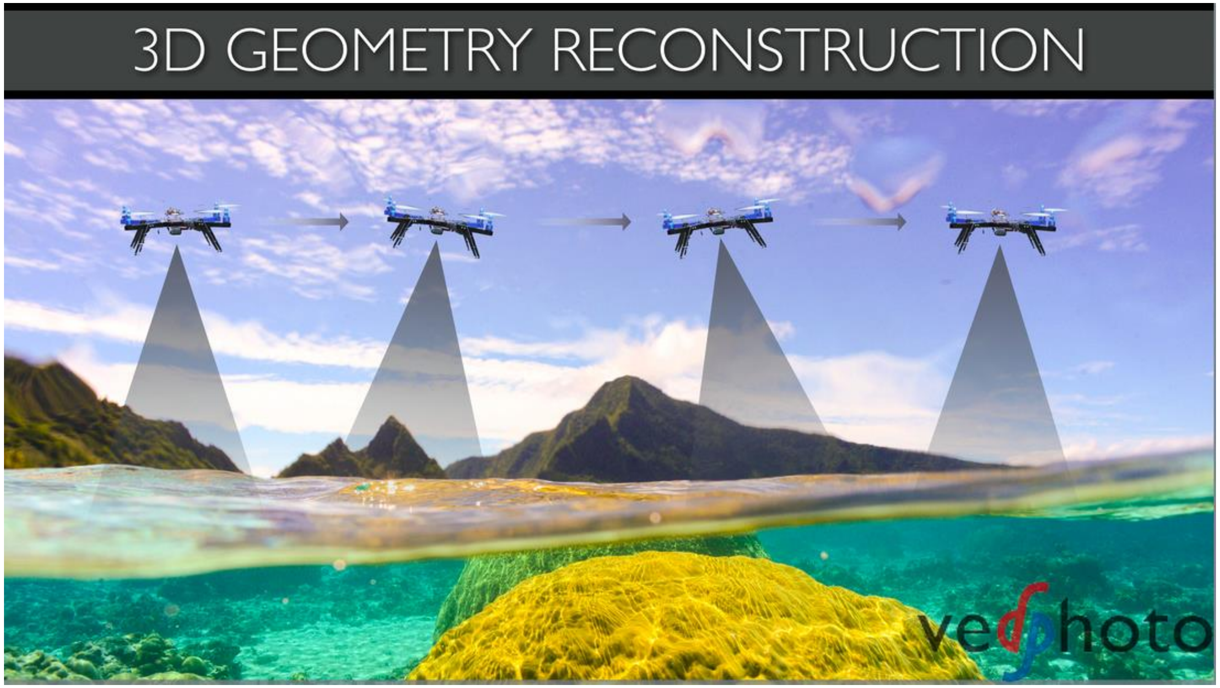
Reference: S. Nag, K.S. Inamdar, J. Jung, "Communication Simulations for Unmanned Aerial Vehicles equipped with Automatic Dependent Surveillance", AIAA Aviation Conference, June 2017

- Coordinated communication of state info between UAV to ground stations using Automatic Dependent Surveillance Broadcast (ADS-B)
- Detailed model of range and signal fidelity of every UAV with respect to operator, other UAVs *and manned aircraft*
- Adding satellites to the model, especially those with intelligent and dynamic pointing abilities, will create a Sensor Web of remote sensing capability.

Decades of EO Aerial Vehicles

Manned and unmanned aerial remote sensing has been prevalent for decades for targeted regions and instruments (called campaigns)

UAV campaign vs. Cubesat video



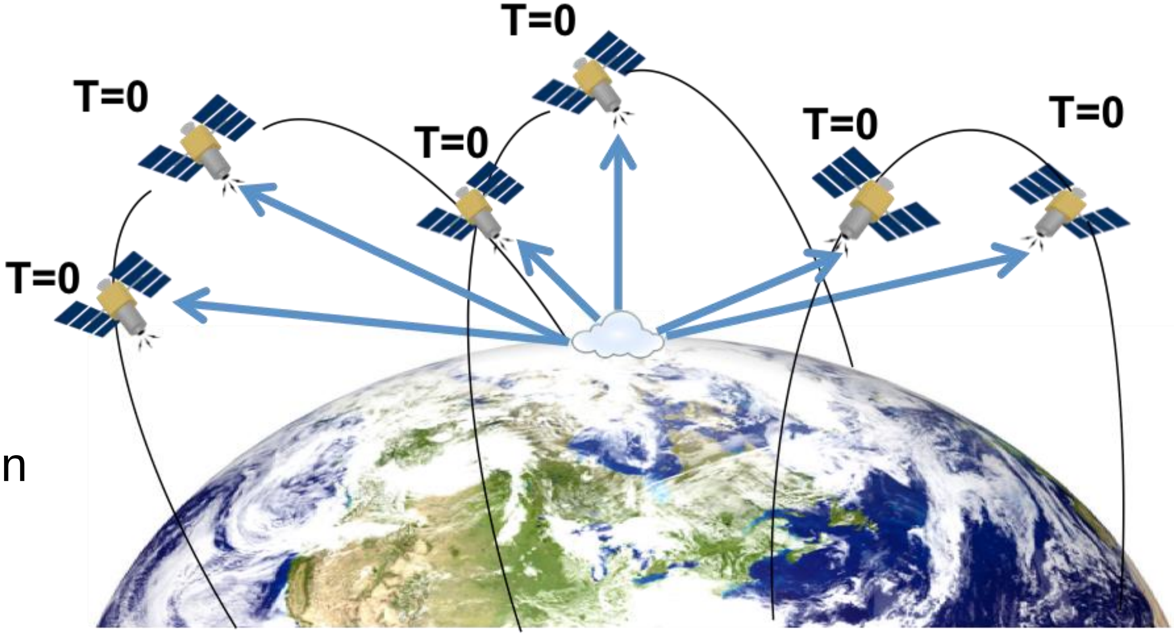
Reference: Chirayath, V., and Earle, S. A. (2016) Drones that see through waves – preliminary results from airborne fluid lensing for centimetre-scale aquatic conservation. Aquatic Conserv: Mar. Freshw. Ecosyst., 26: 237–250. doi: 10.1002/aqc.2654.

- ***UAV similarities with Cubesats:*** Low size, weight and power; quick to design and deploy
- ***Pros over satellites***: Higher resolution, controlled coverage – spatial and temporal, easy to replace,
- ***Cons that can be supported by satellites***: Limited spatial and temporal coverage

Decades of EO Aerial Vehicles

All products in Multi-Angular Remote Sensing are improved by co-pointing formations

Bi-Directional Reflectance Distribution Function Measurements using UAVs vs. satellite formations: A major limitation is the angular under-sampling of the Earth locally. Typically, estimated only locally *using airplanes, UAVs or goniometers.* Causes large uncertainty in albedo, carbon budget, Earth radiation.



A potential solution is formation flight using narrow field of view sensors.

References: S. Nag, C.K. Gatebe, T.Hilker, *"Simulation of Bidirectional Reflectance-Distribution Function Measurements using Small Satellite Formations"*, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, June 2016

S. Nag, C.K. Gatebe, D.W. Miller, O.L. de Weck, *"Effect of Satellite Formation Architectures and Imaging Modes on Global Albedo Estimation"*, Acta Astronautica 126 (2016), 77-97, DOI:10.1016/j.actaastro.2016.04.00

NASA Sensor Webs

To create an interoperable environment for a diverse set of satellite, airborne and ground sensors via the use of software and the Internet. To better understand intrinsically dynamic, complex, and interactive Earth-science processes and delivered globally visa Web 2.0 tools.

Open access tools such as Google Earth can then be used for visualization and calibration.

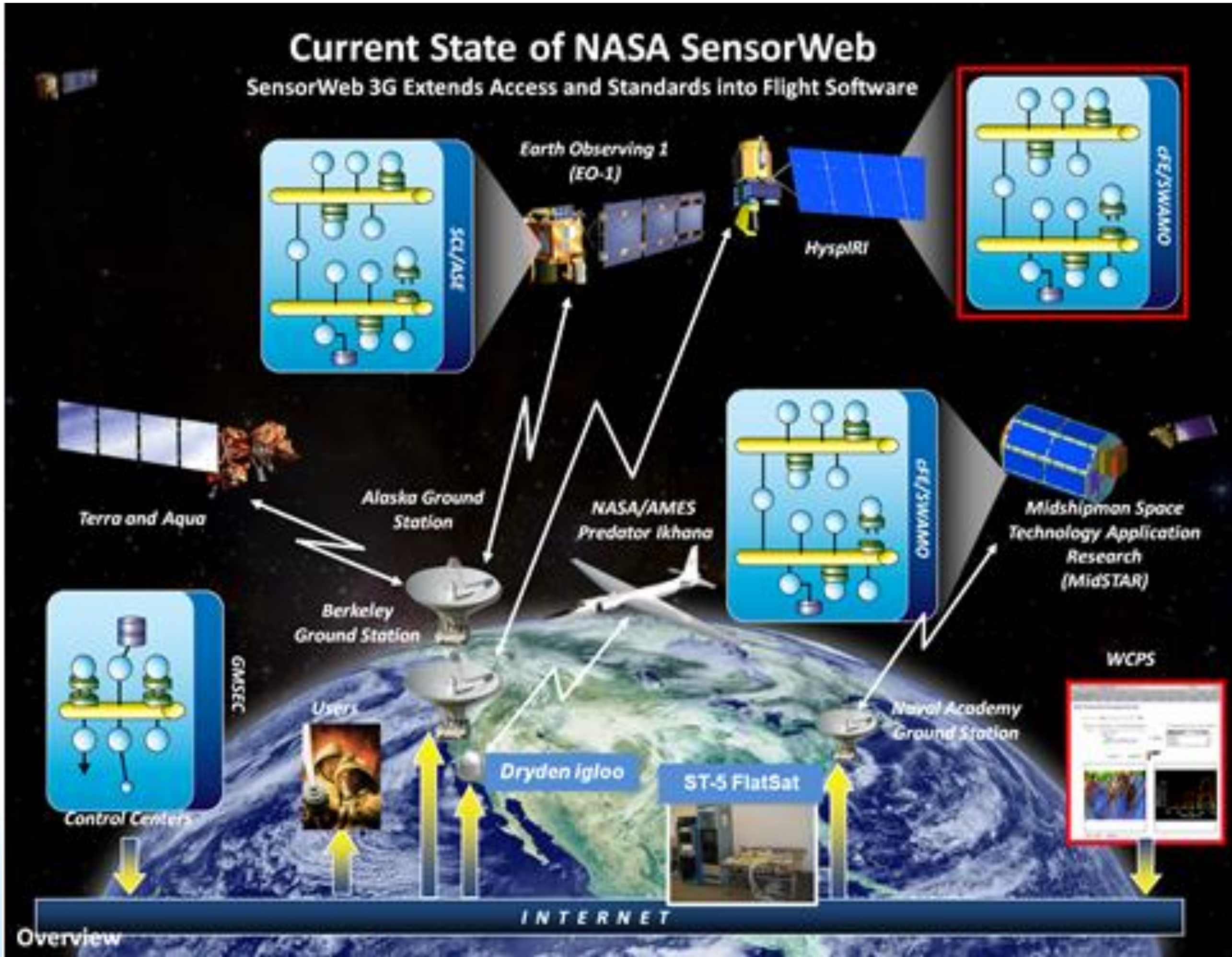
+ UAVs…

+ small satellites/cubesats

+ new technologies in smaller, faster, better, cheaper

Reference:

https://sensorweb.nasa.gov/



Air-Sat Comm Link Budget

#	Parameter	Value	Units	Notes
	Transmitter (Tx) Source ID			
	Tx Power, W	1	Watts	
1	Tx Power, Pt	30.0	dBm	
2	Tx Component Line Losses, Ltl	0.5	dB	
3	Tx Antenna Gain (Peak), Gt	2.0	dBi	Assume: SpaceQuest ANT-100 VHF/UHF Monopole Antenna
4	Tx Pointing Loss, Ltp	3.0	dB	Frontier Lite UHF Radio
5	Tx Radome Loss, Ltr	0.0	dB	
6	EIRP (1-2+3-4-5)	28.5	dBm	
	Propagation			
	Transmission Frequency, f	404.0	MHz	
	Link Range, R	1000.0	km	
	Propagation Factor, n	1.0		
7	Free Space Loss, Ls	144.6	dB	
8	Atmospheric Absorption, Lpa	0.0	dB	
9	Precipitation Absorption, Lpp	0.0	dB	
10	Total Propagation Loss (7+8+9)	144.6	dB	
	Receiver (Rx) Sink ID			
11	Rx Antenna Gain (Peak), Gr	2.0	dBi	Assume: SpaceQuest ANT-100 VHF/UHF Monopole Antenna
12	Rx Polarization Loss, Lrpol	0.0	dB	Frontier Lite UHF Radio
13	Rx Pointing Loss, Lrp	3.0	dB	
14	Rx Radome Loss, Lrr	0.0	dB	
15	Received effective carrier power (6-10+11-12-13-14)	-117.1	dBm	
16	Additional Receiver Chain Gain	2.4	dB	
17	Effective Carrier Power to Receiver (15+16)	-114.7	dBm	
18	Maximum Receiver Input Power	0	dBm	
19	High Receiver Input Margin (18-17)	114.7	dB	
20	Minimum Receiver Input Power	-150.0	dBm	
21	Low Receiver Input Margin (17-20)	35.3	dB	
	Noise			
22	Standard Thermal Noise, kT	-174.0	dBm/Hz	
23	Rx Noise Bandwidth, W	41.9	dBHz	
24	Rx Noise Figure, NF	9.5	dB	
25	Effective Noise Power (22+23+24)	-122.5	dBm	
	Result			
26	Received CNR (17-25)	7.8	dB	
27	Implementation Loss	3.0	dB	Assumed value
28	Available CNR (26-27)	4.8	dB	
29	Uncoded Baseband Data Rate	2000	bps	
	Modulation Type (select)	QPSK		**Note:** check NTIA assumed system parameters on *Background* tab
	Modulation Order (M)	4		
30	$\log_2(M)$	2		
31	Coding Rate (k/n)	1.000		Assume: No coding
32	Coded Baseband Data Rate (29/31)	2000	bps	
	Modulation Symbol Rate, Rs	1000	sps	
33	Modulation Symbol Rate, Rs [32/30]	30.0	dBsps	
34	Received Es/No (28+23-33)	16.8	dB	
35	Received Eb/No (34-[30]-[31])	13.7	dB	
36	Desired BER	0.000010		
37	Required Eb/No	10.0	dB	Run Solver to Generate the Required Eb/No for this modulation
38	Margin (35-37)	3.7	dB	type and desired BER

Noise Bandwidth Determination		
NTIA Necessary		
Bandwidth:	12500	Hz
Expansion	125%	
System		
Bandwidth:	15625	Hz

Rx Noise Figure Determination (at input to receiver)		
G/T	3.0	dB/K
Tsys	33.7	dBK
NF	9.5	dB

Setting up Required Eb/No solver Information			
BER(Eb/No)	-0.000010	Eb/No	11.00

Up to LEO range using a 1 W peak transmitter at 2 Kbps and a commercial UHF antenna. Can be uplink air2sat (for tracking relay) or downlink sat2air (for tasking)

UAV-Sat Case Study and Challenges

Proposed Demonstration:

- UAVs, with complementary instruments w.r.t satellites, hover or wait at operator ground station within an hour's flight radius of pre-defined ground calibration targets
- Satellite (or each in constellation) processes images of locations immediately to indicate geographic coordinates of the image and cloud cover %
- Satellite selects the images that need calibration (onboard processing) and broadcasts its coordinates (communication); UAV is expected to pick up the request signal
- UAV flies to the broadcasted calibration target and makes measurements by flying around the spot at multiple altitudes to capture BRDF without cloud cover obstruction and with minimal time delay
- UAV flies back to operator ground station with data, which can be used for calibrating the later downloaded satellite images

Summary

- Small sats in large numbers allow scalability therefore collaborations and market flexibility, resilience therefore graceful degradation, low cost therefore risk appetite
- Small sats, constellations. Autonomous re-planning and agile control are new technologies for Earth Observation and better science measurements, aside of being great tech demos and opportunities for education
- UAVs have supported the Earth sciences for decades, but very locally and over small time periods. They can be better operated with satellite help and can help support satellite observations
- Dynamic calibration of satellite imagery, for cloud cover and BRDF compensation, using UAVs is an ideal demonstration of the concept of a sensor web
- Research collaborations in any aspect of this effort (UAVs vs. balloons? UAV simulations/data sharing? Geo-referencing or image processing? Multi-asset scheduling? Other case studies?) is very welcome.

Questions?

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