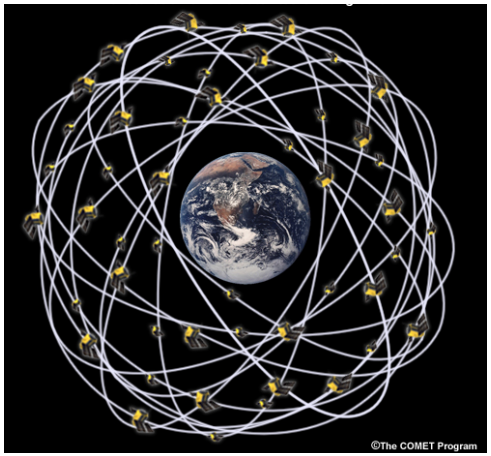
TAKING SCIENCE BY SWARM



Presentation to the NASA 30 Year Roadmap Committee

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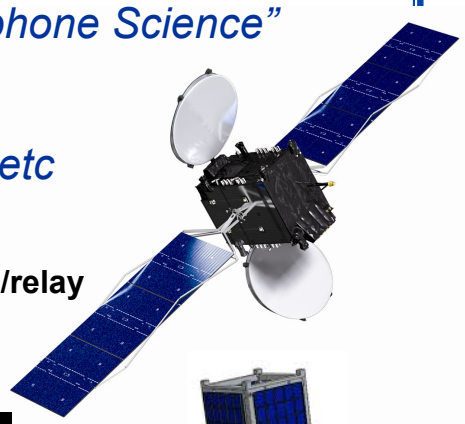
Swarm-sat Concept

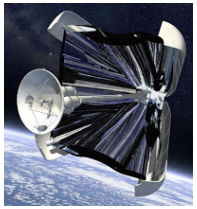
- **Network of satellites with common functionality that can be configured for multi-spectral and multipurpose operation**
  - *An analogy is cell phones running various applications: "Smartphone Science"*
- **Set of simple integrated highly efficient core functions**
  - *Power, communications, attitude sensing, GPS, camera/video, etc*
- **Simple re-usable common interfaces**
  - *Low development time, very flexible*
  - *Mix of sizes and capabilities*
- **Plus one or more specialized instruments**
  - *Telescopes/detectors: optical, radio, X-ray, UV, IR, etc*
  - *Gravitational reference sensor*
  - *Particle detector*
  - *Low noise/long lifetime micro-thruster*
- **Separation by function enables additional optimization**
  - *Cryogenic detectors separate from warm instruments*
  - *Magnetically sensitive instruments requirements only for host spacecraft, etc*
  - *Precision pointing vs relaxed attitude control*



Comm/relay

SMOS: phased array

Cubesat



Pancake or "umbrella"-like

Scientific Motivation

- **For some cases, better science with a distributed network of simple instruments vs a single complex instrument**
  - *Angular resolution depends on the total baseline*
  - *Sensitivity depends on the number of apertures (total collecting area)*
  - *Co-location of different instruments should help reduce systematic errors*
  - *Similar idea for astrophysics as hyperspectral imaging is for Earth Science*
  - *Substitute location knowledge of components and processing for precise placement*

Ground-based Examples:

- **LOFAR: 20,000 omni-directional antennas to achieve high sensitivity, wide field of view, and high angular resolution from 10-250 MHz**
- **ALMA: uses ~ 50 12 meter antennas to get 10 milliarcseconds angular resolution from 350 μm to 10 mm**

Space-based proposal

- **Array of gravitational wave detectors plus multi-band electromagnetic counterpart detectors**
- **Some applications may use "hive plus swarm" (mothership) architecture**
  - *External occulter -- High angular resolution X-ray telescope*

Simple Model

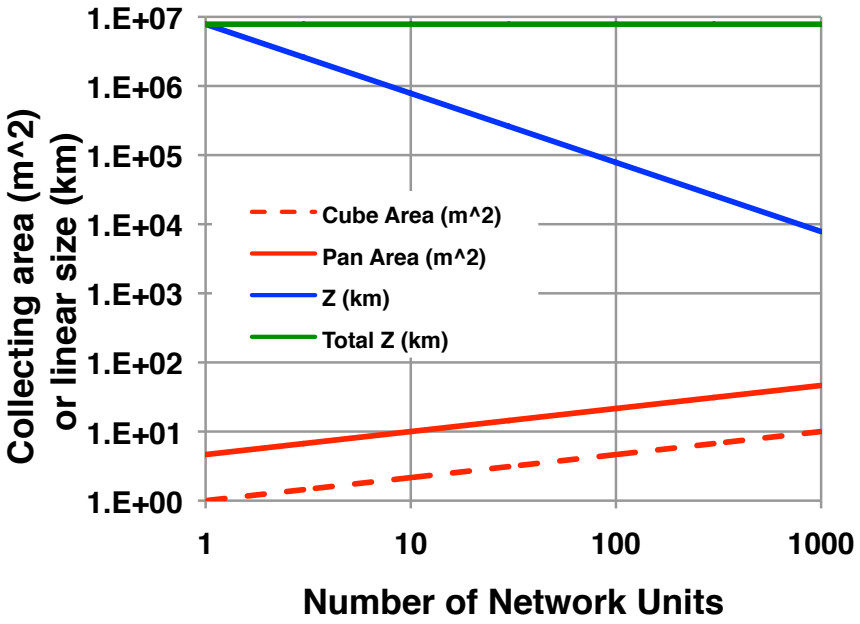
CUBE

Unit Mass (kg)	N	L (m)	Power (W)	Collecting Area (m^2)	Z (km)	Total Z (km)
1.0	1000	0.10	4.50	10.00	782	782,305
3.3	300	0.15	10.04	6.69	2,608	782,305
10.0	100	0.22	20.89	4.64	7,823	782,305
33.3	30	0.32	46.61	3.11	26,077	782,305
100.0	10	0.46	96.95	2.15	78,230	782,305
333.3	3	0.69	216.34	1.44	260,768	782,305
1000.0	1	1.00	450.00	1.00	782,305	782,305

PANCAKE

Unit Mass (kg)	N	L (m)	Power (W)	Collecting Area (m^2)	Z (km)	Total Z (km)
1.0	1000	0.22	20.89	46.42	7.82E+03	7.82E+06
3.3	300	0.32	46.61	31.07	2.61E+04	7.82E+06
10.0	100	0.46	96.95	21.54	7.82E+04	7.82E+06
33.3	30	0.69	216.34	14.42	2.61E+05	7.82E+06
100.0	10	1.00	450.00	10.00	7.82E+05	7.82E+06
333.3	3	1.49	1004.15	6.69	2.61E+06	7.82E+06
1000.0	1	2.15	2088.71	4.64	7.82E+06	7.82E+06

(look at trends, not absolute numbers)



- Fixed total launch mass
- Power generation scales with area
- Separation is comm limited

- For science, pancake form factor appears better than cubes
- Sensitivity increases with N
- Angular resolution constant or decreases with N
- Power source and thermal management are key

Swarm System Characteristics

- **Favorable Economics: Incremental Deployment is possible**
  - *Drop satellites off from one main launch vehicle adapter (bus)*
  - *Incremental growth as budget allows and sensitivity requires*
  - *instrument complexity relies on electronics so may follow Moore's Law (detectors don't)*
- **Adaptable observing mode (run different "apps")**
  - *Wide-field sky-sweep survey mode*
  - *Rapid reconfigure for narrow beam location determination*
  - *Phased array methods allow for multiple simultaneous beams*
- **Co-location of multiple detectors may reduce systematics**
  - *Different wavelength detectors operate from a common coordinate system*
  - *Calibration by observing known sources*
- **Technology challenges:**
  - *Efficient algorithms for networking, data processing, operation, ranging*

"CD" storage as analog for launch vehicle for "pancake" satellites. Other geometries possible

Example (over the top): gravitational wave detector array plus co-located radio and X-ray telescope arrays

X-ray array

High angular resolution radio array finds electromagnetic counterpart

Earth

gravitational wave array

Sun

comm relay or mothership

Radio telescope array

*See for example: Ultra-high precision cosmology from gravitational waves, Cutler & Holz, arXiv:0906.3752v1 (2009)

Summary

- Networks of small satellites may out-perform large complex satellites for some applications
- Incremental deployment as budget allows and sensitivity requires
- Moore's Law may apply if electronics costs dominate
- Separation by function enables instrument optimization
- Self-healing and self-networking
- Distributed processing may reduce comm requirements
- Adaptable and flexible observing modes
- Co-location of multiple detectors reduces systematics