Space and Earth:

How the Search for MH370 Reveals the Ubiquity – and Limitations - Of Surveillance From Space

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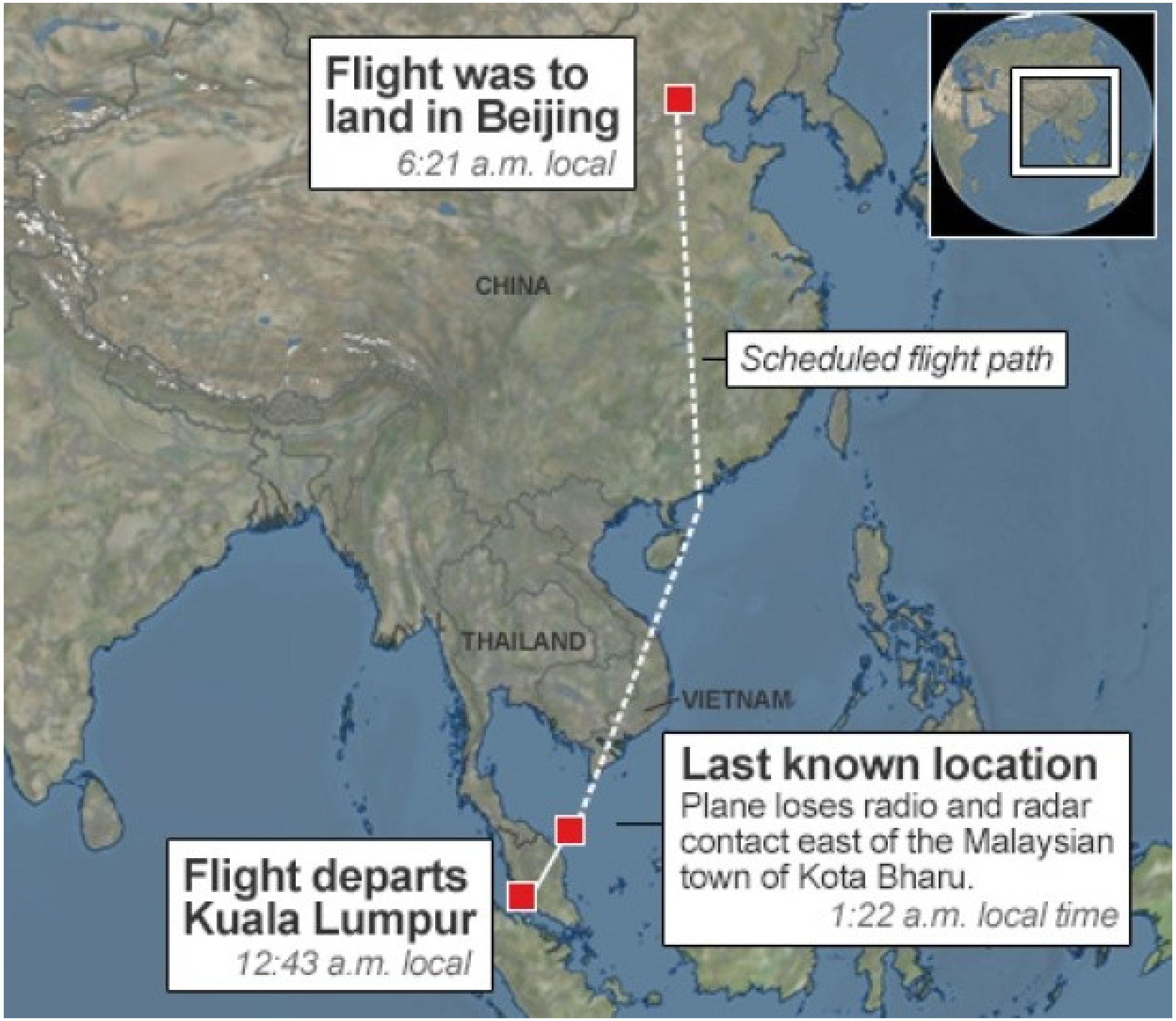
Part 1: MH370 goes missing
- and INMARSAT finds a clue

Ocean pic credit:
patternsofnatureblog.com B.Ellis

2014 Mar 7: Boeing 777-200ER aircraft, flight MH370 from KUL (Kuala Lumpur, Malaysia) to PEK (Beijing) loses contact at 1719 UTC, 40 min into a 6 hr flight

The plane, with 239 people aboard, has not been seen since



Credit: Canadian Broadcasting Corp

AHeenen via Wikipedia

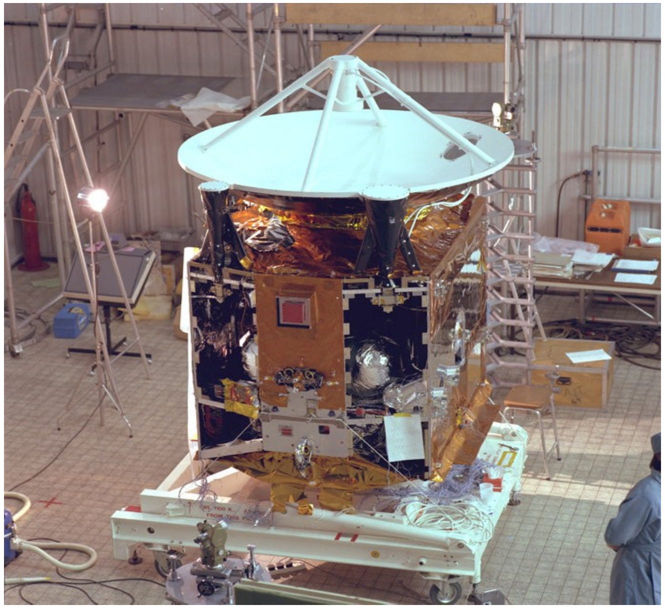
No radio contact
Nothing on radar
A complete mystery

… then came a surprising breakthrough

Communications satellites!

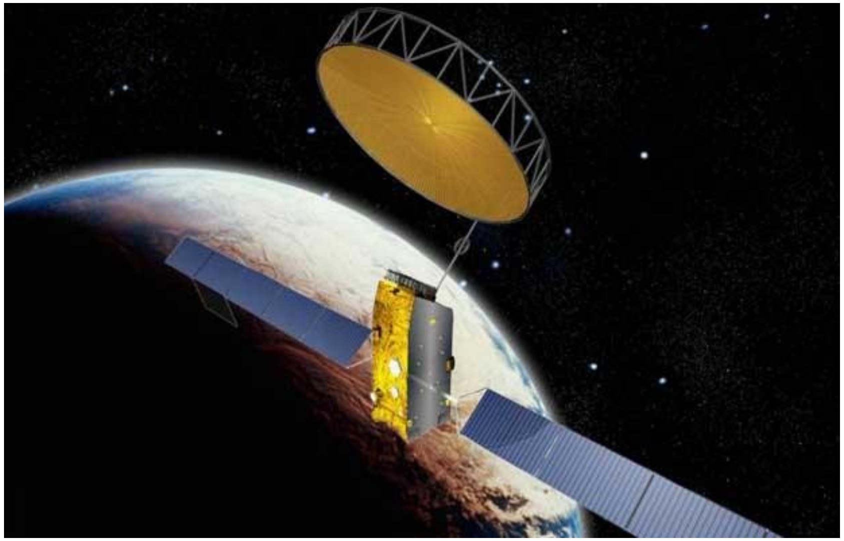
Hackney, London: (1 km N of St Paul's Cathedral)
INMARSAT headquarters

INMARSAT was the International Maritime Satellite Organization
until it was privatized in 1999



MARECS A under assembly in Stevenage, UK in 1981 – first maritime comms satellite for INMARSAT

US-built INMARSAT 3 F1 satellite
L-band communications payload (MMS-UK)
Launched from Cape Canaveral, Apr 1996
Stationed over Indian Ocean at 64 E, May 1996



Newer generation INMARSAT-4 satellite
4 in orbit 2005-2013

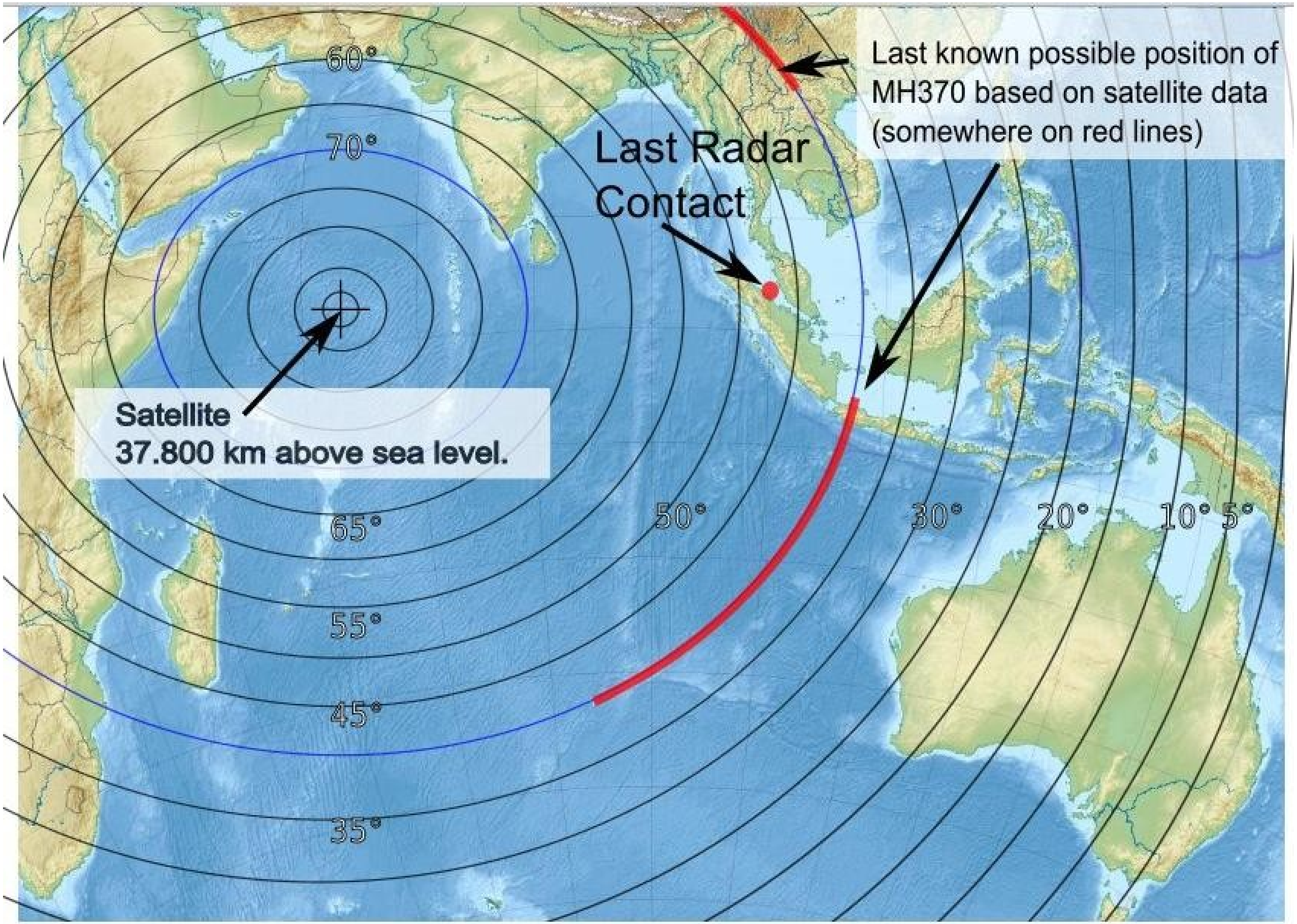
Inmarsat hosts Rockwell Collins ARINC system “ACARS”
Aircraft Communications Addressing and Reporting System

The discussion that follows reports the work of the INMARSAT investigation team:

Chris Ashton, Alan Shuster Bruce, Gary Colledge, Mark Dickinson
The Search for MH370
Journal of Navigation, 2014
doi:10.1017/S037346331400068X

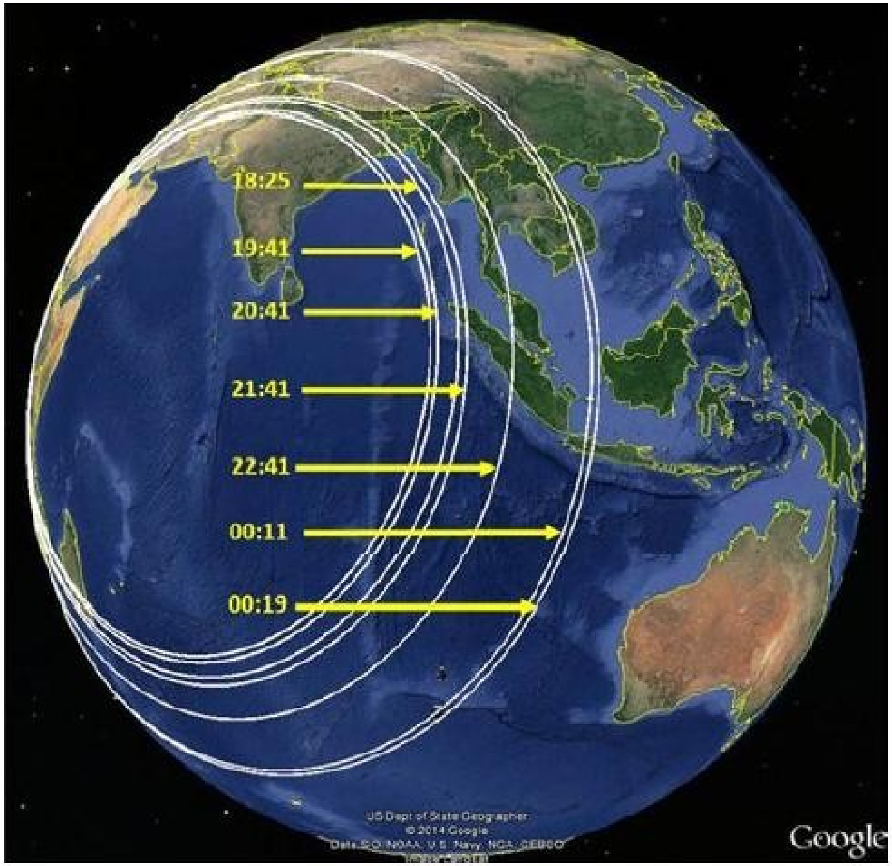
supplemented by the work of the Australian Transport Safety Bureau (ATSB)
MH370 – Flight Path Analysis Update
ATSB Transport Safety Report, AE-2014-054, 8 Oct 2014

Australian Government
Australian Transport Safety Bureau



ACARS “switched off” by crew (or failed off?) but system stayed logged on to satellite – hourly 'pings' give the round trip travel time   satellite-aircraft-satellite

Time	Channel Name	Ocean Region	GES ID (octal)	Channel Unit ID	Channel Type	SU Type	Burst Frequency Offset (Hz) BFO	Burst Timing Offset (microseconds) BTO
....								
48 C-Channel and 1 P-Channel messages moved into separate below table (see appendix 2) to ease the reading of key events. C-Channel messages have no BTO values								
....								
7/03/2014 23:15:02.032	IOR-3737-21000	IOR	305	6	C-Channel RX	0x30 - Call Progress - Channel Release	219	
00:10:58 - Handshake Request, with response								
8/03/2014 00:10:58.000	IOR-P10500-0-386B	IOR	305	10	P-Channel TX	0x14 - Log Control - Log-on Interrogation		
8/03/2014 00:10:59.928	IOR-R1200-0-36ED	IOR	305	4	R-Channel RX	0x15 - Log-on/Log-off Acknowledge	252	18040
00:19:29 - Log-On Request (reported as a Partial Handshake), initiated from the aircraft terminal								
8/03/2014 00:19:29.416	IOR-R600-0-36F8	IOR	305	10	R-Channel RX	0x10 - Log-on Request (ISU)/Log-on Flight Information (SSU)	182	23000
8/03/2014 00:19:31.572	IOR-P600-0-36FC	IOR	305	10	P-Channel TX	0x11 - Log-on Confirm		
8/03/2014 00:19:32.212	IOR-P600-0-36FC	IOR	305	10	P-Channel TX	0x40 - P-/R-Channel Control (ISU)		
8/03/2014 00:19:32.212	IOR-P600-0-36FC	IOR	305	10	P-Channel TX	Subsequent Signalling Unit		
8/03/2014 00:19:32.852	IOR-P600-0-36FC	IOR	305	10	P-Channel TX	0x41 - T-Channel Control (ISU)		
8/03/2014 00:19:32.852	IOR-P600-0-36FC	IOR	305	10	P-Channel TX	Subsequent Signalling Unit		
00:19:37 - Note that the following R-Channel burst at 00:19:37.443 is the last transmission received from the aircraft terminal								
8/03/2014 00:19:37.443	IOR-R1200-0-36F6	IOR	305	10	R-Channel RX	0x15 - Log-on/Log-off Acknowledge	-2	49660
8/03/2014 00:19:38.407	IOR-P10500-0-386B	IOR	305	10	P-Channel TX	0x15 - Log-on/Log-off Acknowledge		
01:15:56 – Handshake Request - No Response from Aircraft Terminal								
8/03/2014 01:15:56.000	IOR-P10500-0-386B	IOR	305	10	P-Channel TX	0x14 - Log Control - Log-on Interrogation		
01:16:06 - Handshake Request - No Response from Aircraft Terminal								
8/03/2014 01:16:06.000	IOR-P10500-0-386B	IOR	305	10	P-Channel TX	0x14 - Log Control - Log-on Interrogation		
01:16:15 - Handshake Request - No Response from Aircraft Terminal								
8/03/2014 01:16:15.000	IOR-P10500-0-386B	IOR	305	10	P-Channel TX	0x14 - Log Control - Log-on Interrogation		



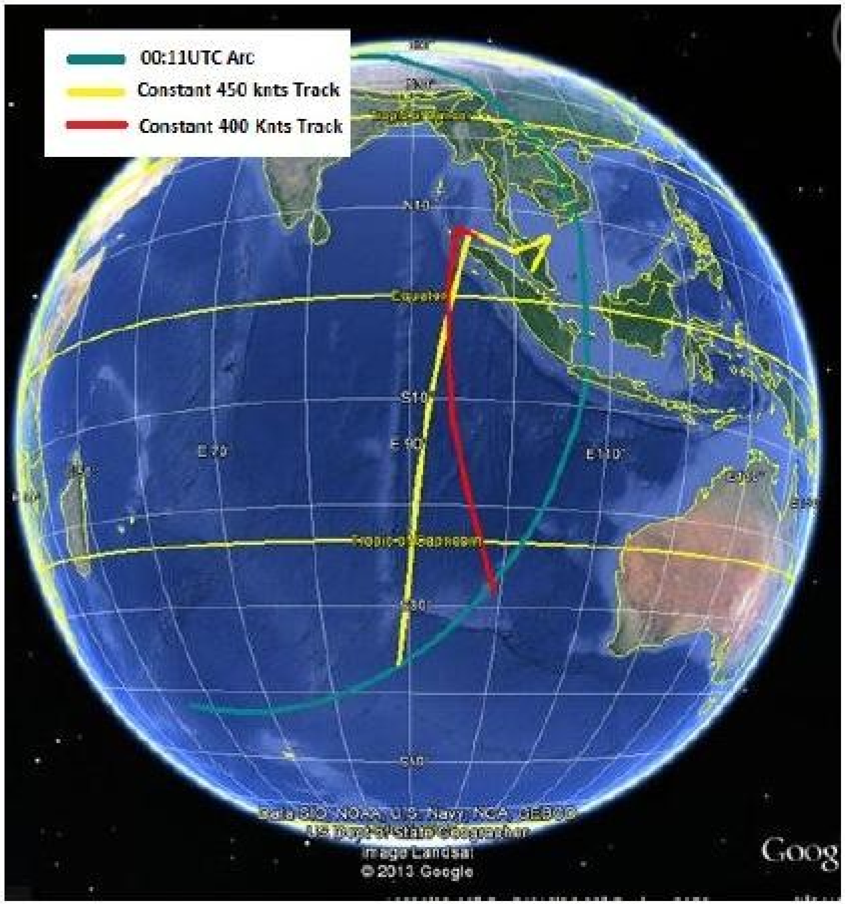
ATSB

Each 'ping' between aircraft and satellite gives a distance to the aircraft corresponding to a ring on the Earth's surface centered on the subsatellite point in the Indian Ocean

The investigative team modelled the motion of the aircraft at constant speed, constant heading with the constraint of intersecting these rings at given times. Lack of angular data and symmetry of problem → 2 solutions

Example Southern Tracks

(tracks ends at 00:11 UTC)



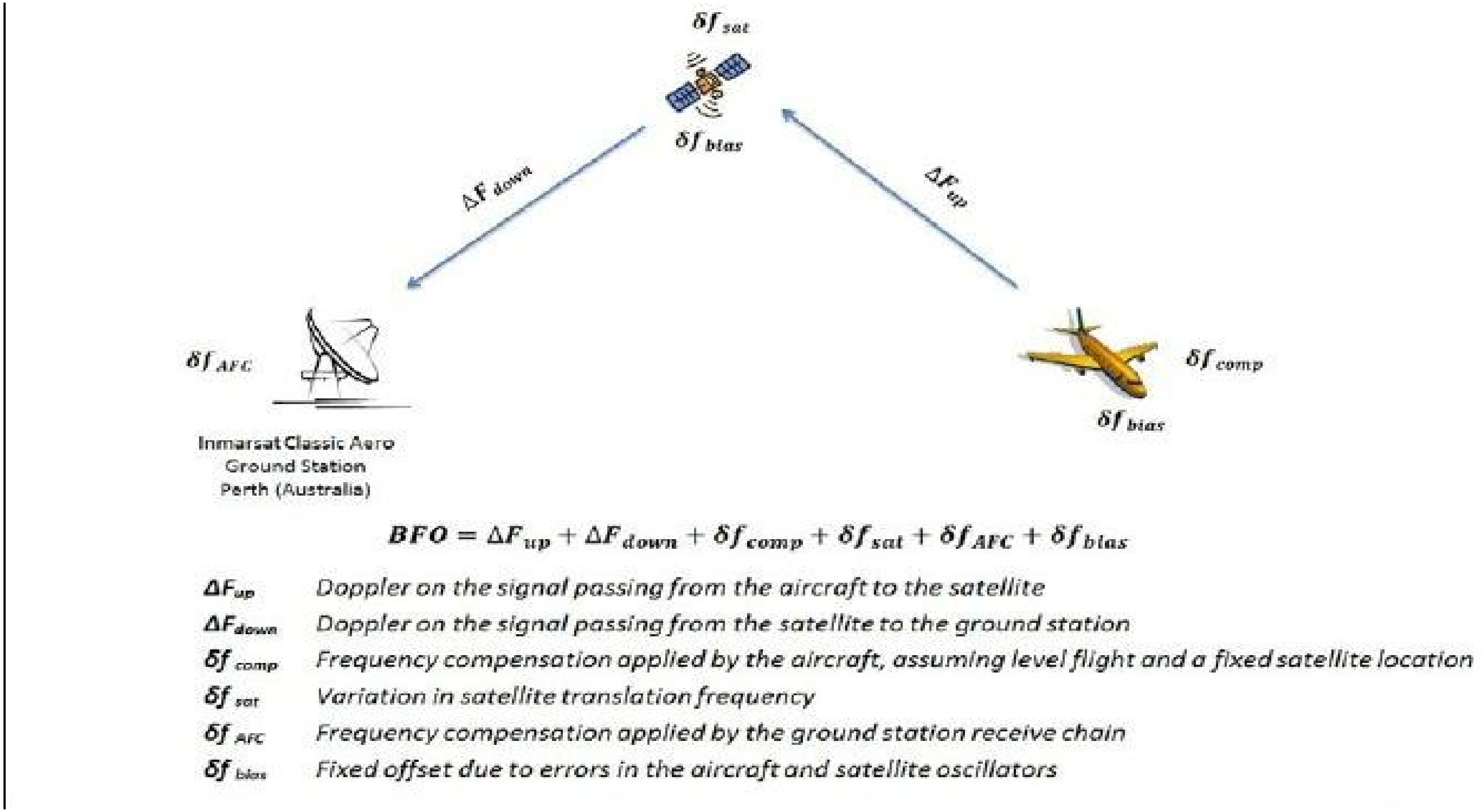
3

Complications:

- calibration errors
- altitude changes by plane
- exact time of turn south
- movement of satellite
- modelling of maximum range cruise (MRC): how far the A/C gets before fuel runs out

Source: INMARSAT

Data: range and range rate versus time
Model: Moving on great circle at constant speed v on heading theta
Fit data to model assuming a given value of v, get theta and final position
Figure shows v = 400 knots (red) and v = 450 knots (yellow)



BTO Burst Timing Offset – records difference in expected and actual signal round trip time satellite-aircraft-satellite
Gives satellite-aircraft range

Source: SATCOM Working Group, INMARSAT

BFO Burst Frequency Offset
Compares received frequency to expected frequency after Doppler and electronics corrections (error ~ 7 Hz ~ 5kph)
Gives satellite-aircraft radial velocity

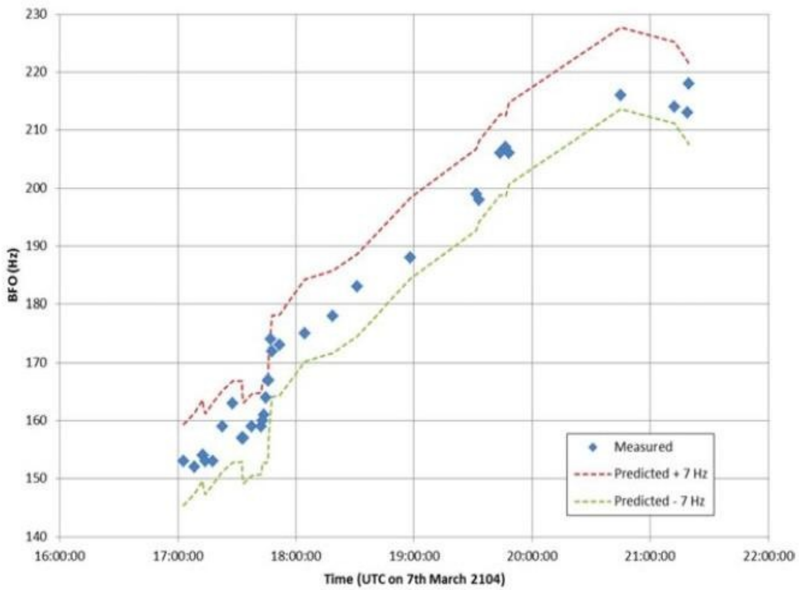


Figure 15. Burst Frequency Offset Validation (Amsterdam Flight).

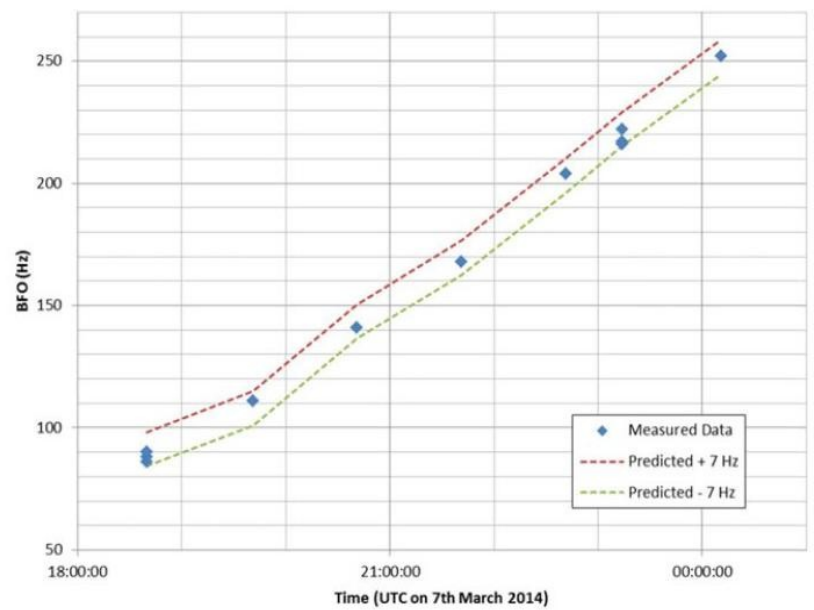
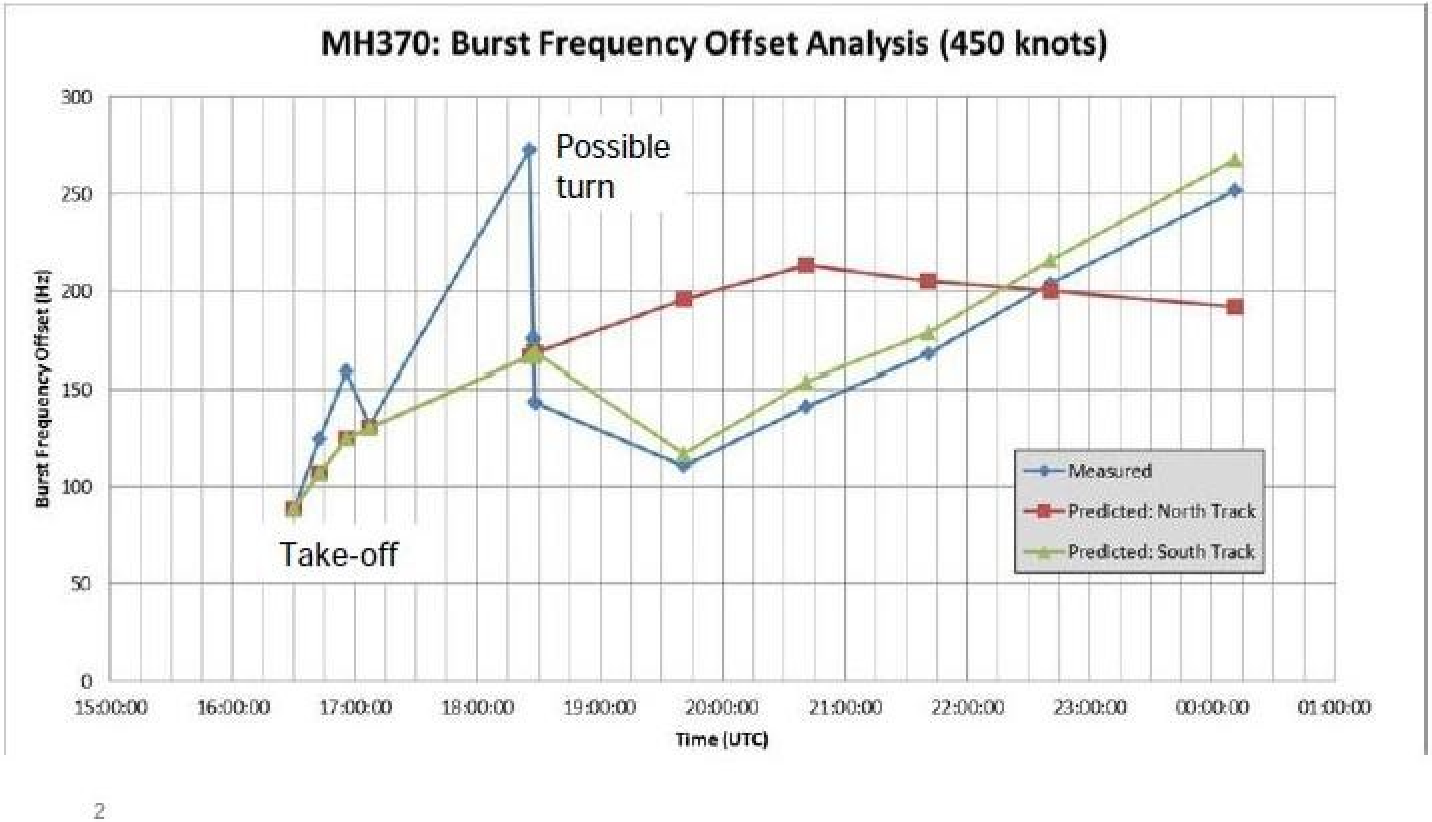


Figure 16. BFO Results for Example Flight Path.

Predicted Doppler versus time
for known flight path
MH21 Kuala Lumpur-Amsterdam
same day as MH370

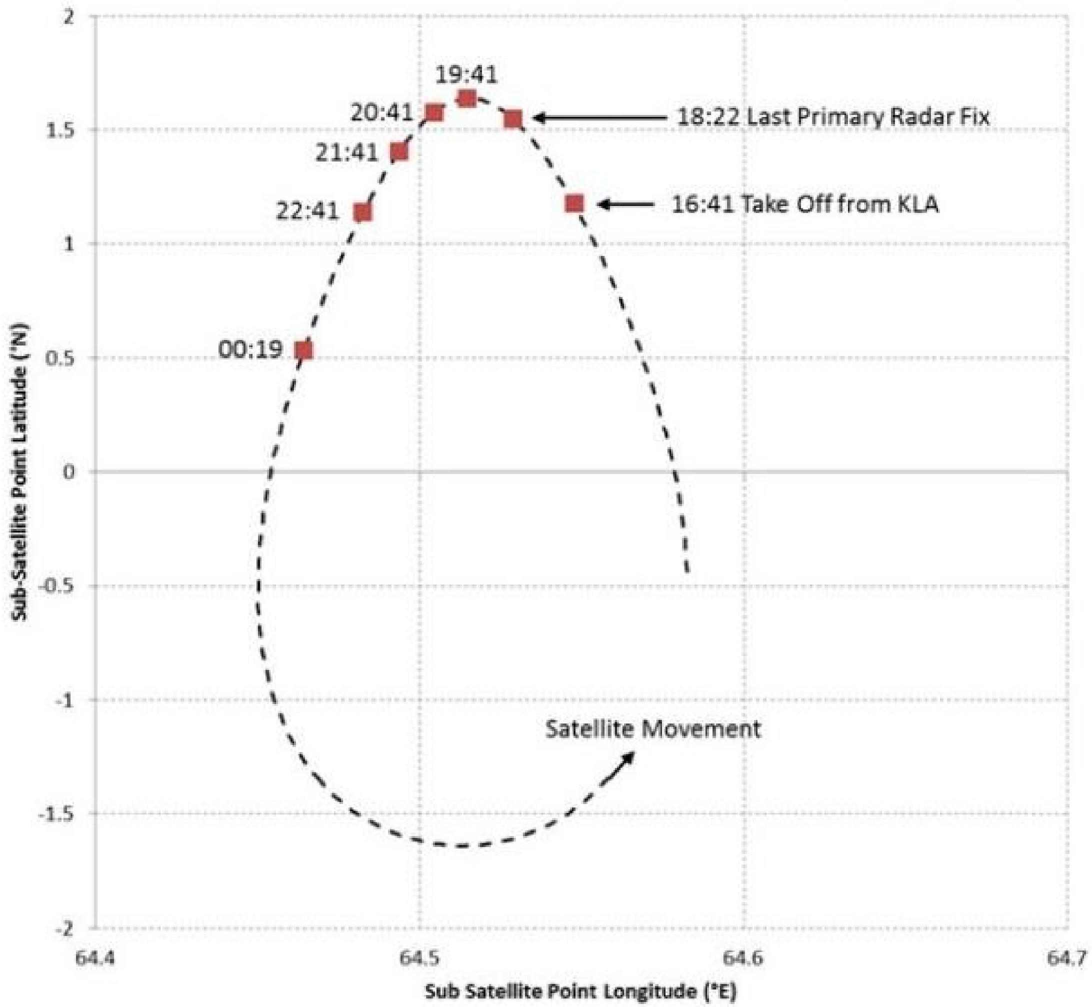
Example model ground track
for MH370, +/- 7Hz errors,
compared to MH370 data
points- for later part of flight

MH370 measured data against predicted tracks



Source: INMARSAT - as released in spring 2014

Blue points are the actual data (Doppler shift in Hz of MH370 rel to sat)
Includes earlier times than previous plot
Green points are the fit using v=450 knots
(Get two solutions for each v, a northern and southern one;
southern one clearly fits better)



Satellite moves +/- 1.5 deg N/S of equator (Ashton et al 2014)

This must be taken into account

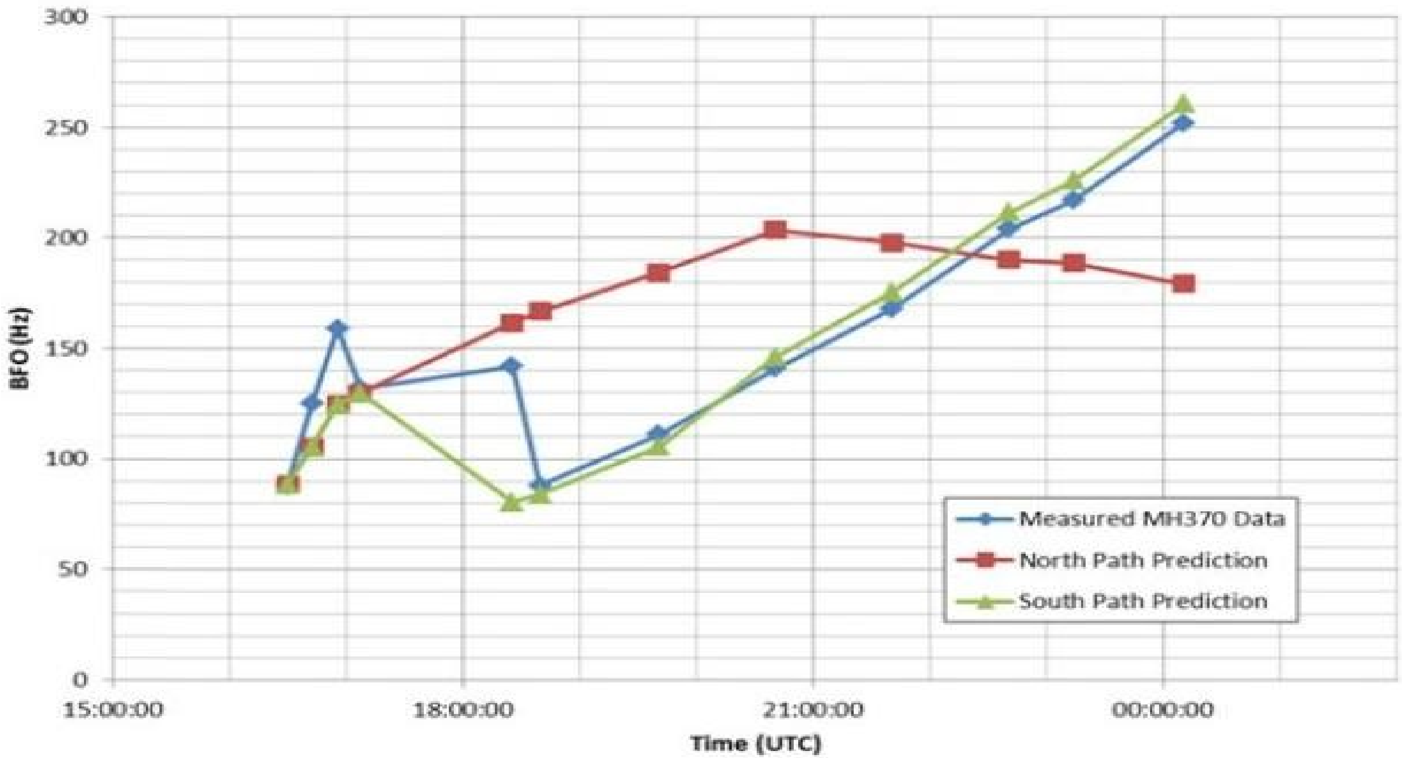
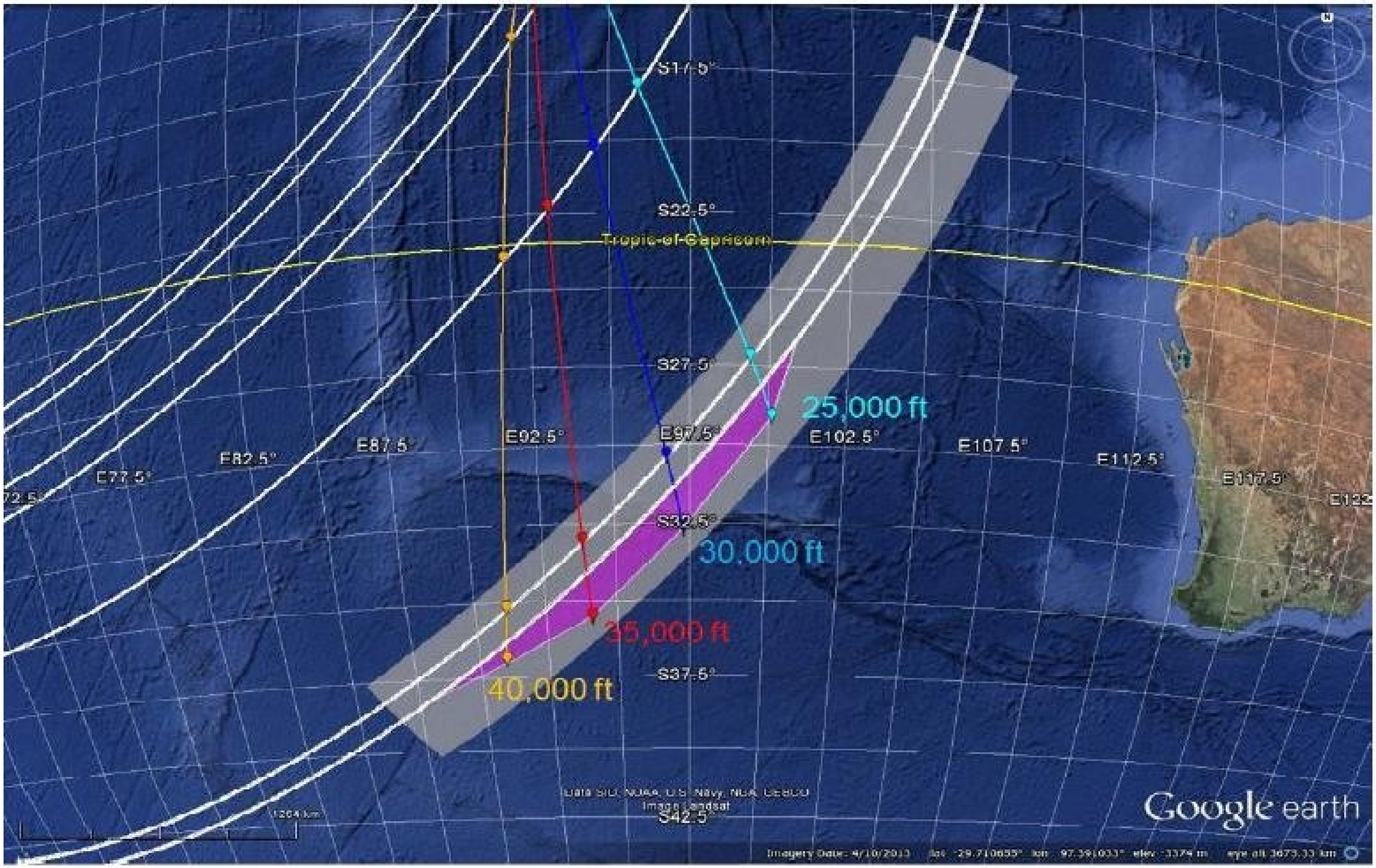


Figure 14. BFO Results using Refined Model.

Source: INMARSAT - as updated in paper, fall 2014
- better satellite motion model, correction for satellite eclipse thermal effects, improved calibration of ground station electronics

Blue points are the actual data (Doppler shift in Hz of MH370 rel to sat)
Green points are the fit using v=450 knots
(Get two solutions for each v, a northern and southern one;
southern one clearly fits better)

Sensitivity of final location to assumed aircraft altitude



ATSB update, Oct 2014

Future developments

Aug 2014:
EUTELSAT announces that the new EUTELSAT 172B satellite to be launched over the Pacific in 2017 will be the first to carry a Ku-band payload dedicated to airplane connectivity with coverage beams targeted on busy Asia/Pacific air corridors

Space-Based ADS-B: Automatic Dependent Surveillance, satellite based data relay from airplanes

- **to be provided on Globalstar-2 satellites now in orbit**
- **ITU expected to approve 1090MHz air-to-space ADS-B signal in Nov 2015**
- **Iridium 2nd generation satellites to carry Aireon ADS-B receivers (launch 2015 on Falcon 9)**
- **Aalborg University (Denmark)/GomSpace GATOSS ADS-B demo cubesat satellite launched 2013 for tests**
- **Worldwide coverage by 2017?**

Part 2: The (imaging) search from space

Missile Early Warning systems – large infrared telescopes, usually at GEO altitude

USAF/TRW Defense Support Program (DSP) and its successor
USAF/Lockheed Martin Space-Based Infrared System (SBIRS)
PVO (Russia) /Lavochkin Upravlaemiy-Sputnik-K 'Oko” (Eye) satellites

- able to see Scud missile launches in Middle East conflicts
- should have seen an exploding airliner if there was one?
- US DoD implies not seen

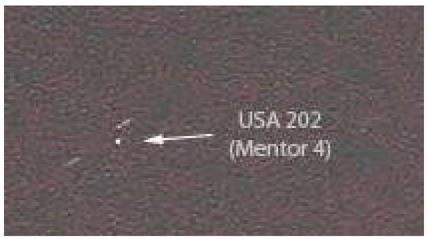
SBIRS

DSP

Oko

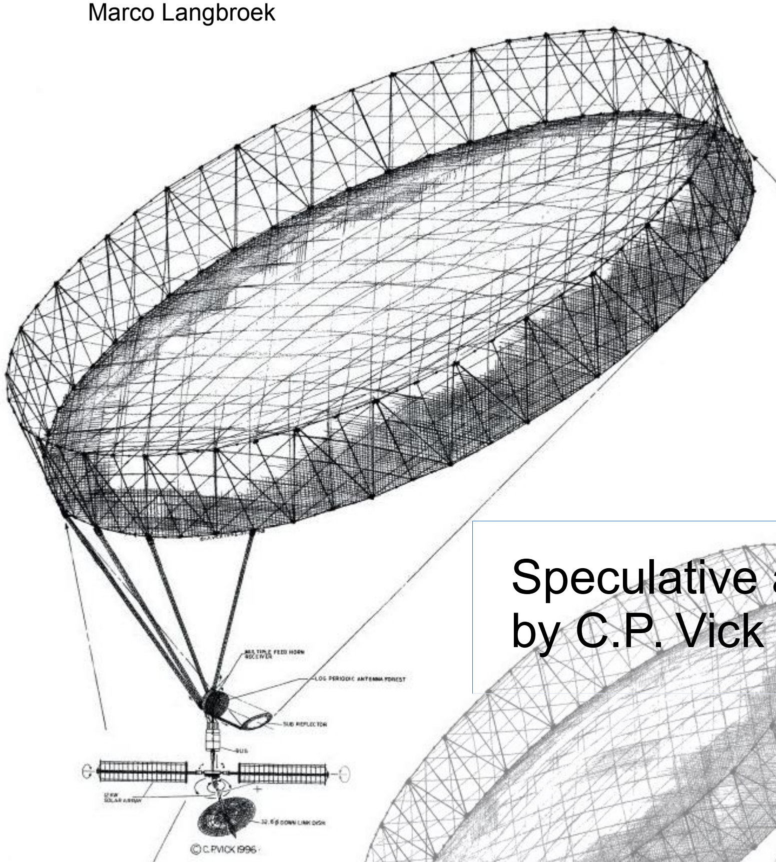
Signals Intelligence Satellites

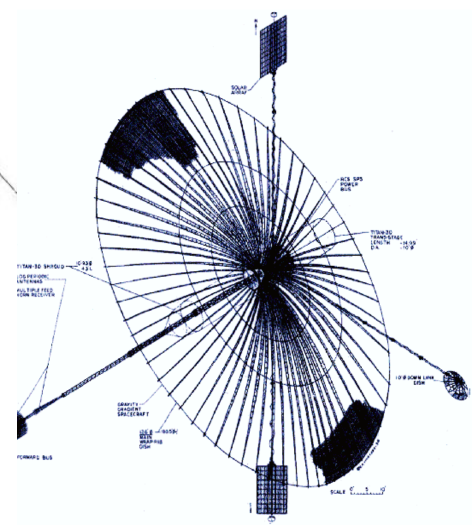
The most highly secret space systems. Includes large radio telescopes in GEO pointing down... dishes possibly up to 75 metre dia!
Include COMINT (communications intelligence) capability
But probably not usually targeting commercial airliners
If they detected any transmissions, they are not saying!



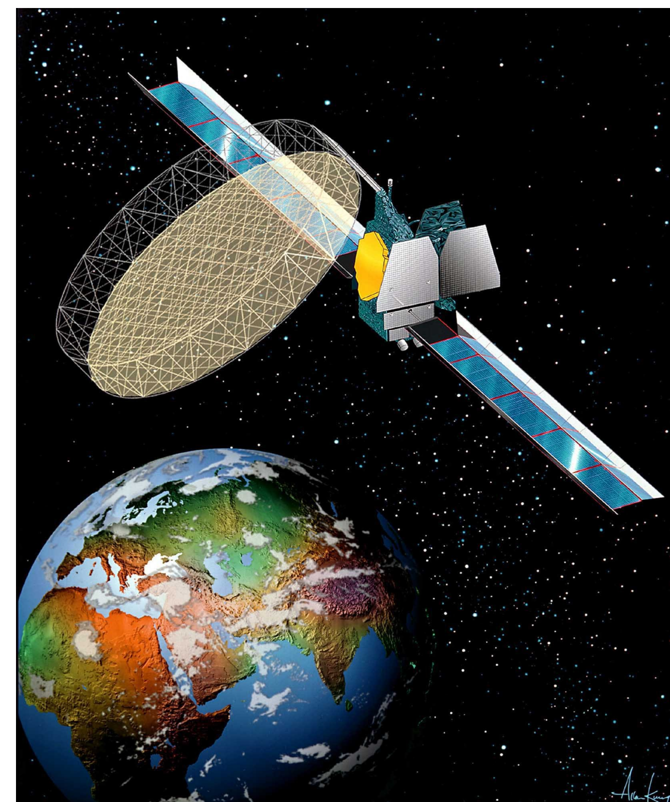
mag 8 apparent magnitude in GEO (bright!)

Marco Langbroek



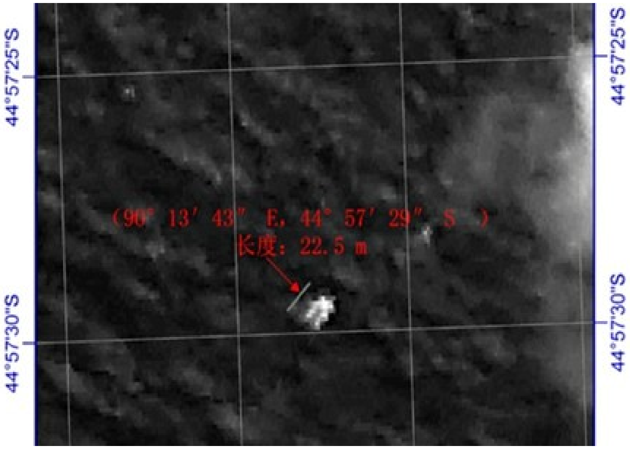


Speculative art by C.P. Vick

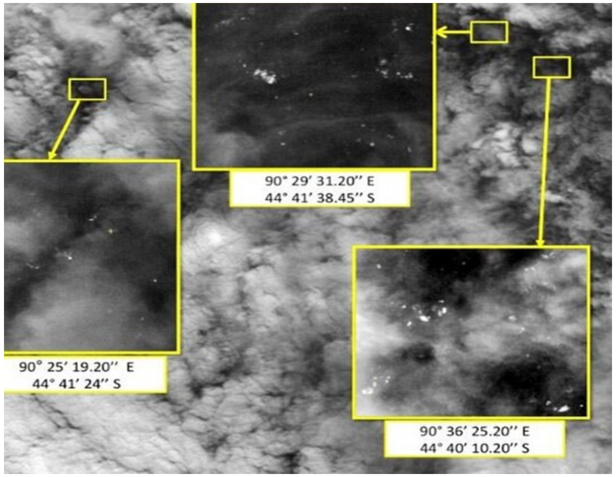


Civilian cellphone satellite with 12 metre antenna

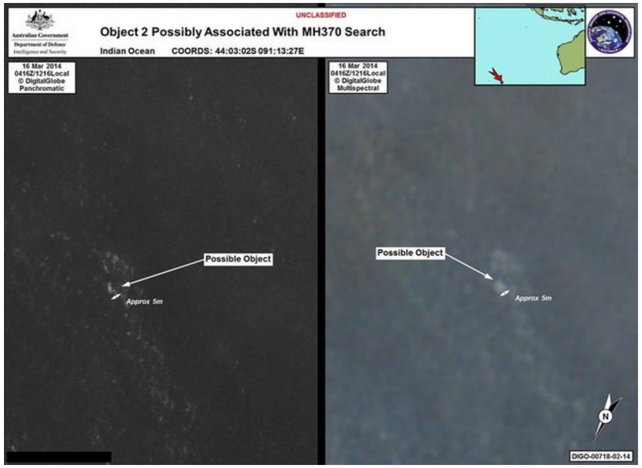
MH370 debris candidates in satellite imagery



Gao Fen 1 (China)



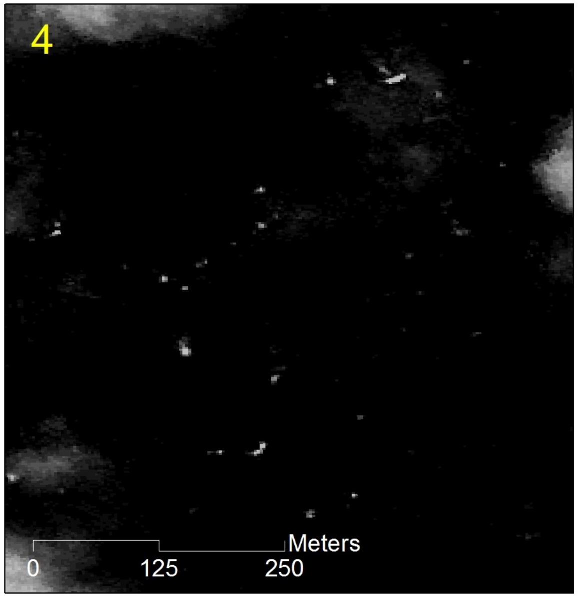
SPOT-6 (France)

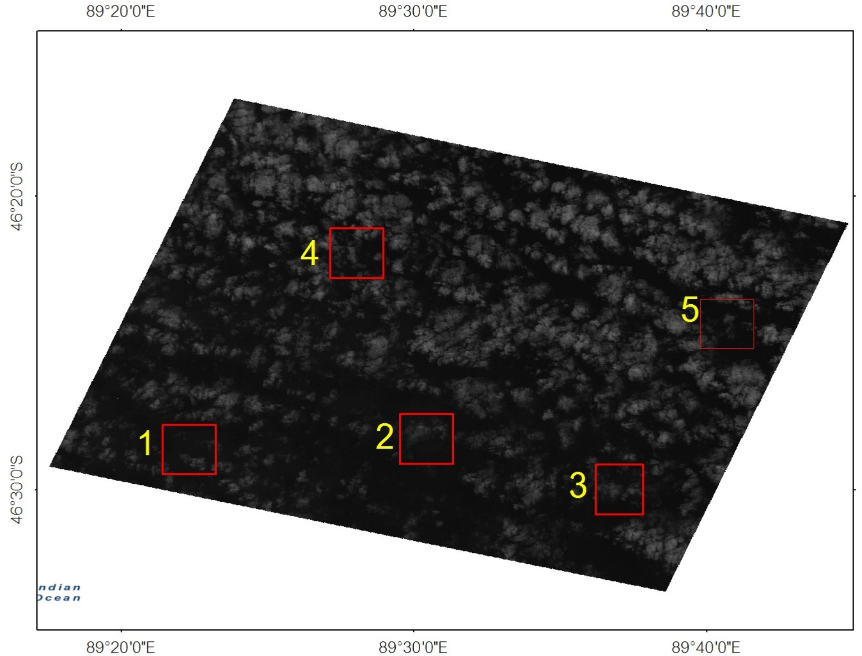


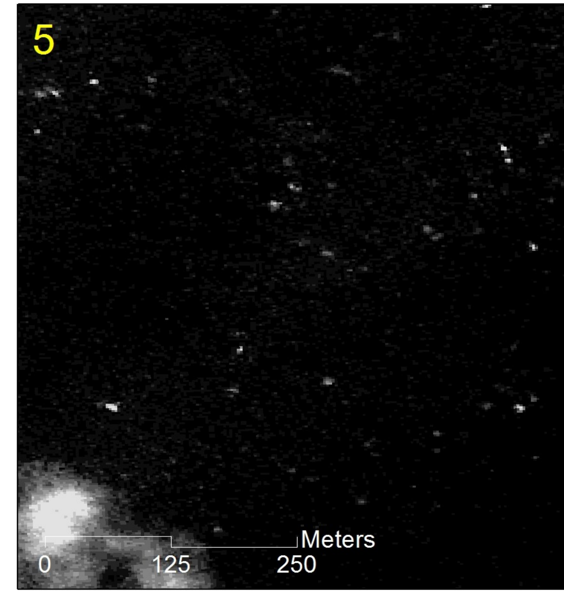
Worldview-2

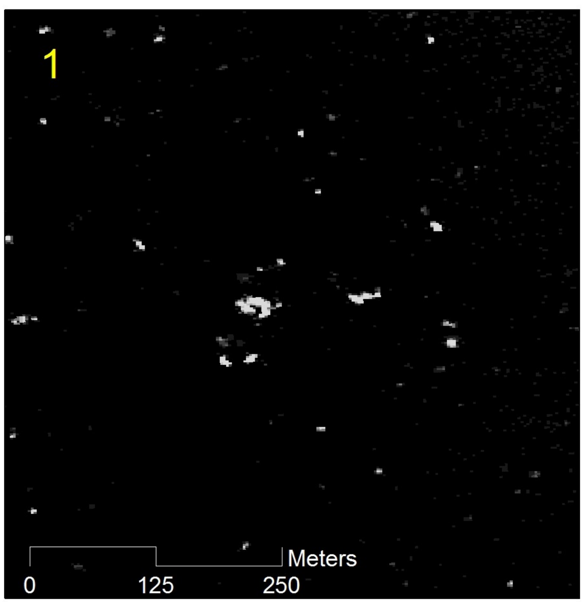
DigitalGlobe, USA

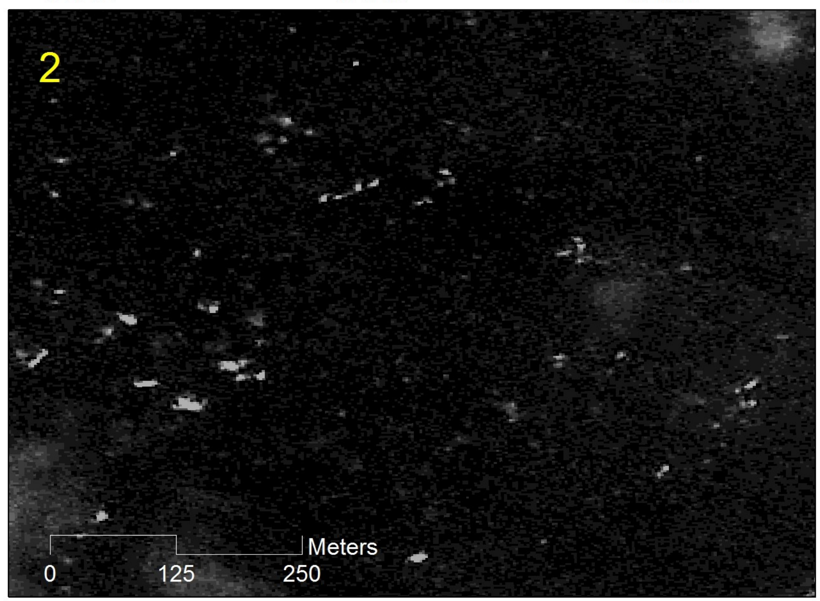
THAICHOTE imagery acquired on March 24, 2014 03:07 (UTC) In the Indian Ocean

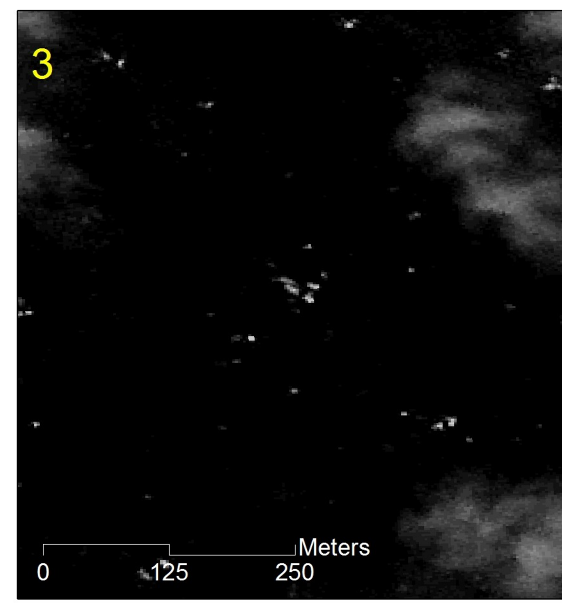












SATELLITE NAME: THAICHOTE (GISTDA,THAILAND)
MODE: PANCHROMATIC (2 Meters Resolution)
DATE: 2014-03-24
TIME: 03:07:56.153985 (UTC)
SATELLITE INCIDENCE ANGLE: 26.982451

ELLIPSOID..............................WORLD GEODETIC SYSTEM 1984
GRID................................GEOGRAPHIC COORDINATE SYSTEM
VERTICAL DATUM..MEAN SEA LEVEL
HORIZONTAL DATUM..............WORLD GEODETIC SYSTEM 1984
PRINTED BY..GISTDA

GEO-INFORMATICS AND SPACE TECHNOLOGY DEVELOPMENT AGENCY (PUBLIC ORGANIZATION)

MINISTRY OF SCIENCE AND TECHNOLOGY, THAILAND

“Thaichote”? Really?

Many developing countries now have imaging satellites
Surrey Satellite in England started selling 100 kg imaging satellites to developing countries in the 1990s

Other European satellite manufacturers now in the game – Thaichote was built by Astrium-Toulouse for the Geo-Informatics and Space Technology Development Agency of Bangkok

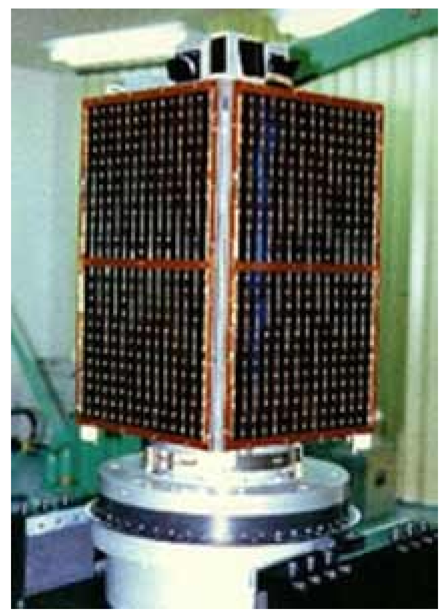

Alsat (Algeria) 2002


Tiungsat (Malaysia) 2000


Fasat (Chile) 1998

Posat (Portugal) 1993


Bilsat (Turkey) 2003


Uribyol
S Korea 1992

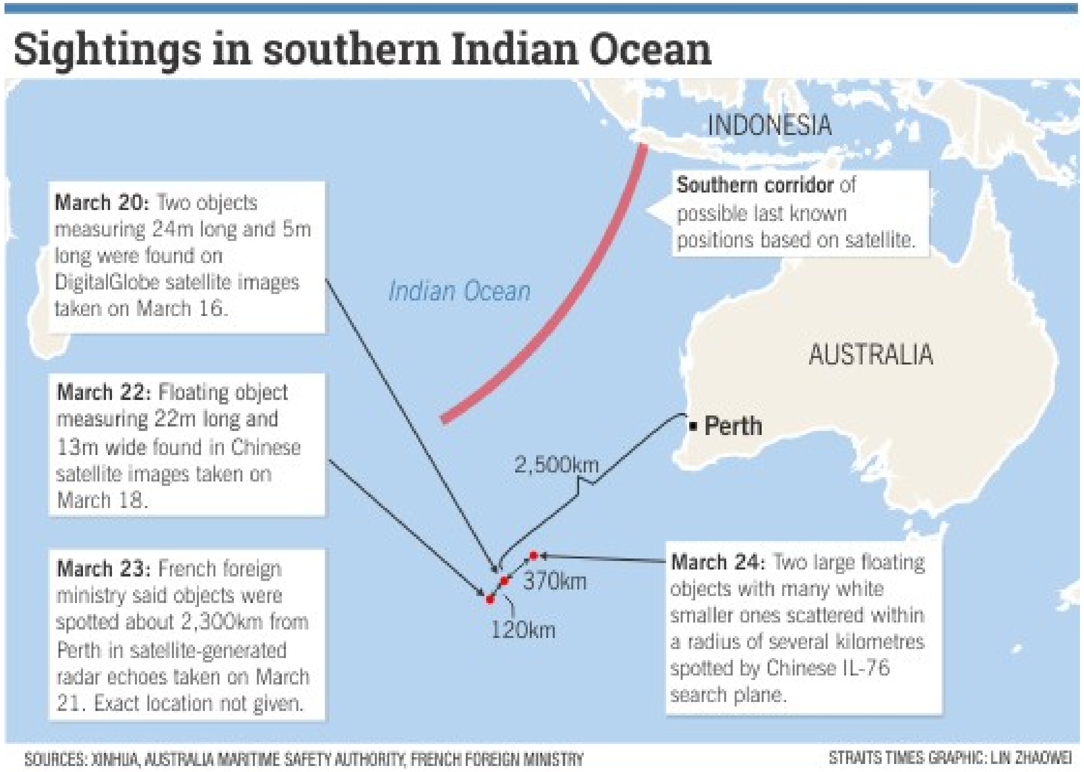
Nigeriasat-2 2011

What was the result of the searches by imaging satellites?

There is a LOT of debris and garbage floating around the Indian Ocean...

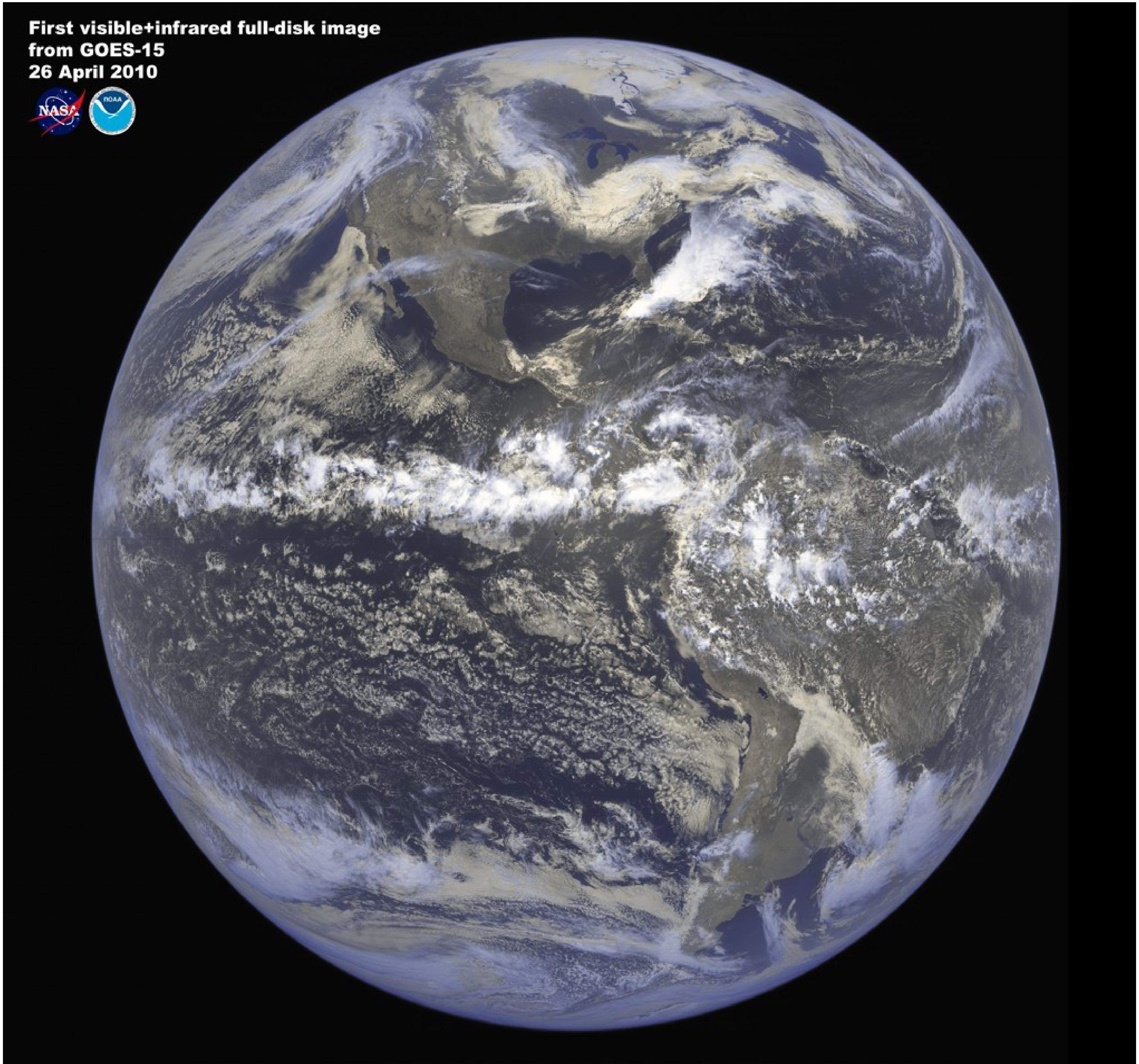
… but apparently none of it is from MH370

Why was nothing seen?

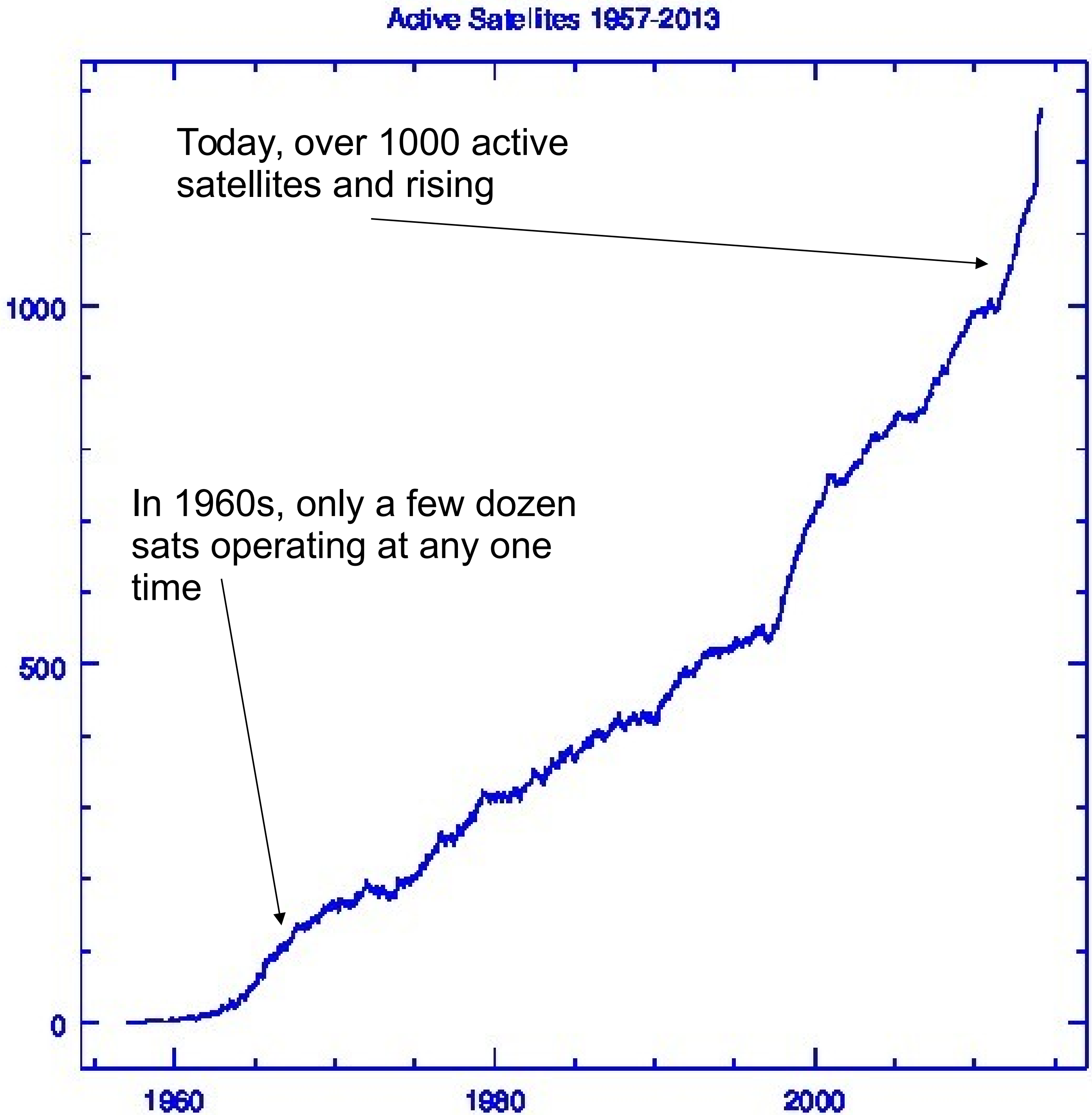


Part 3: Imaging satellites in 2014
and the myth of global imaging surveillance

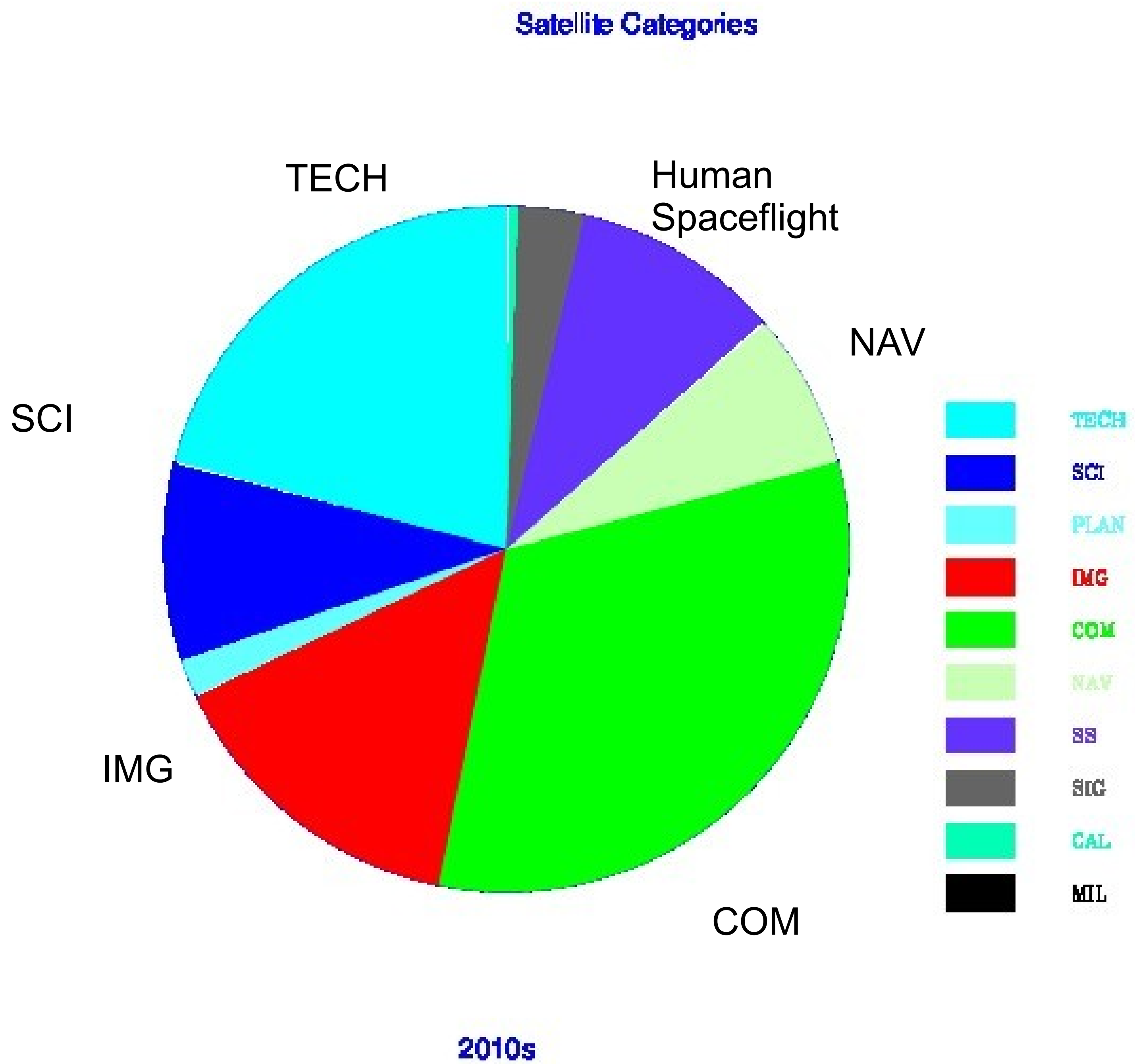
Global coverage - low resolution



Small area, high resolution: 40cm image from Worldview-3
Top of the line DigitalGlobe civilian imaging satellite

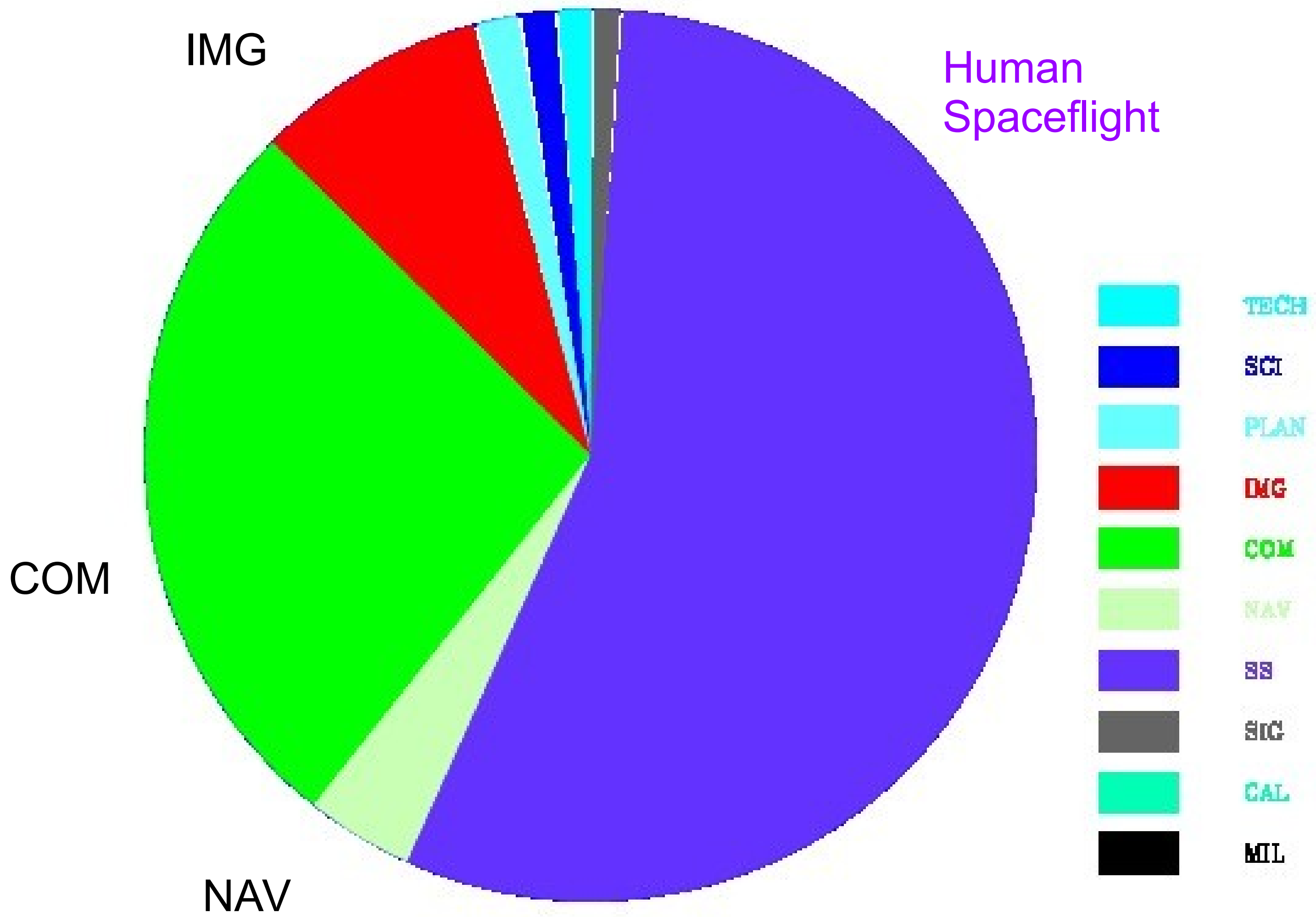


McDowell 2014: http://planet4589.org/space/log/stats.html



In the 2010s, most sats are either communications or imaging; technology development (including student satellites) also a big sector

Satellite Tonnage (including human spaceflight)



2010s

By mass however, human spaceflight dominates – comms still next
Tech/student satellites vanish, they are mostly little cubesats which don't weigh much

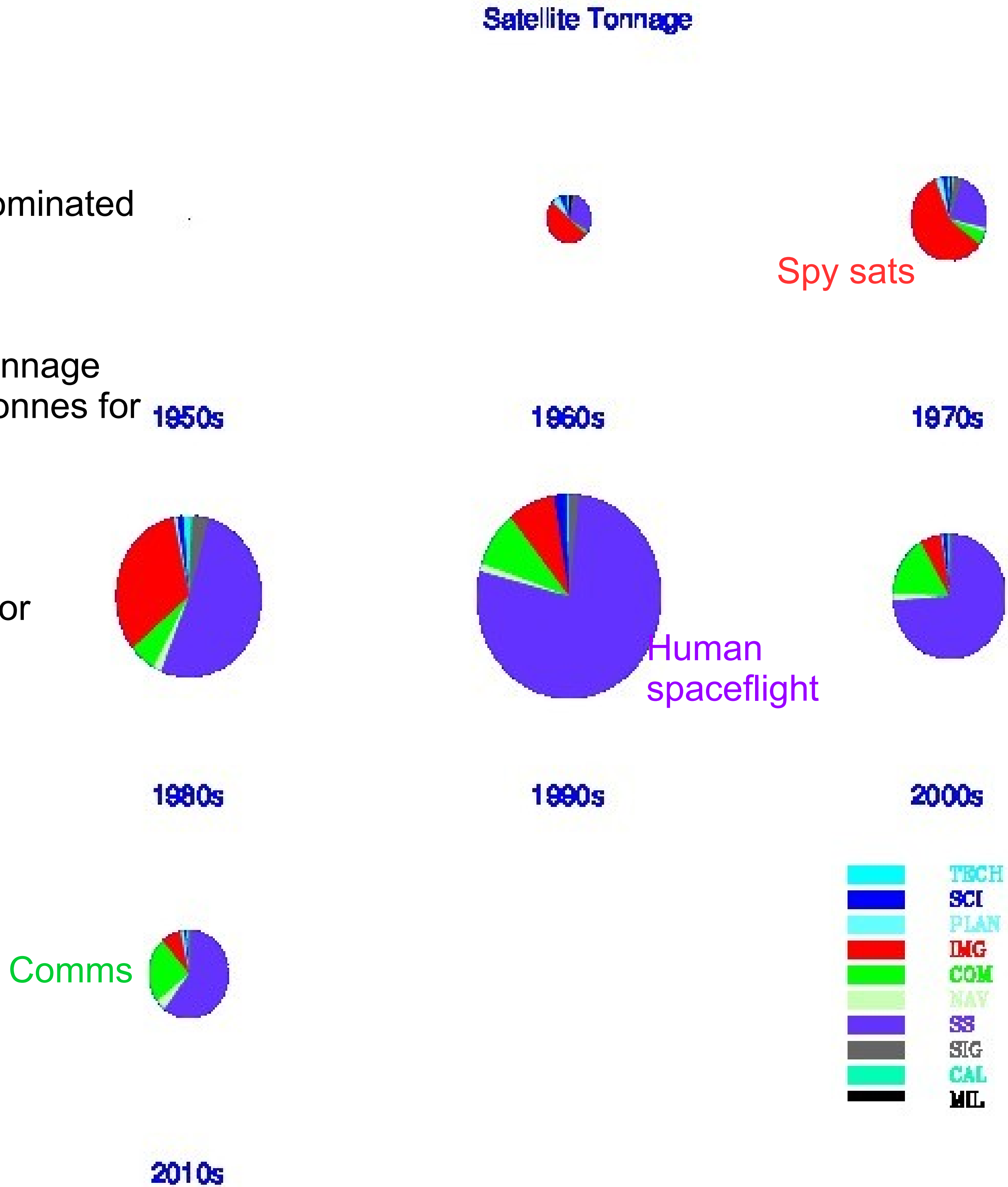
4-yr total 900 t robotic, 1100 t 6 x Shuttle + ISS/PRC

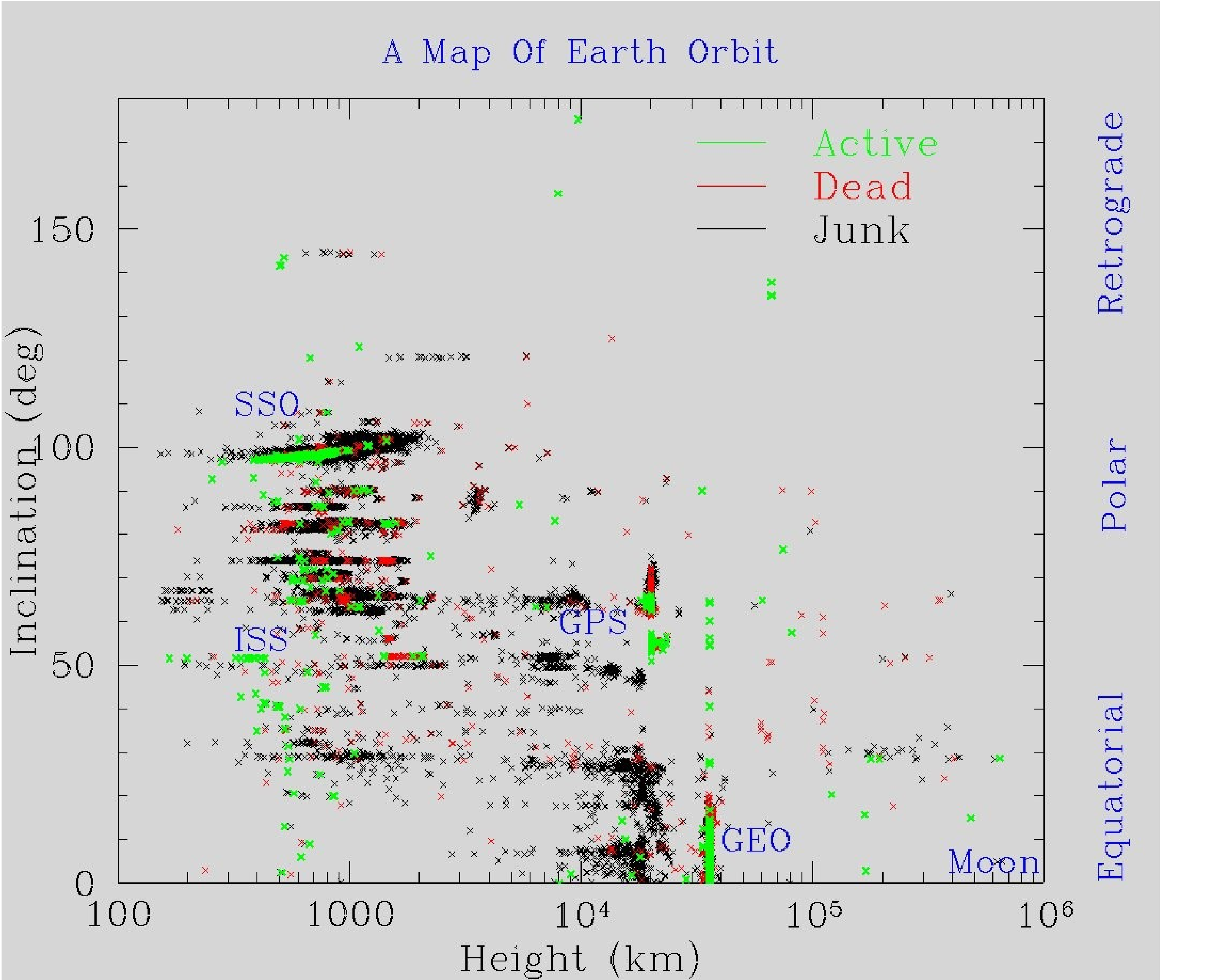
Decade by decade:

Red:
Imaging (spy sats) dominated in cold war

Purple:
Human spaceflight tonnage huge in 1990s (100 tonnes for each Shuttle)

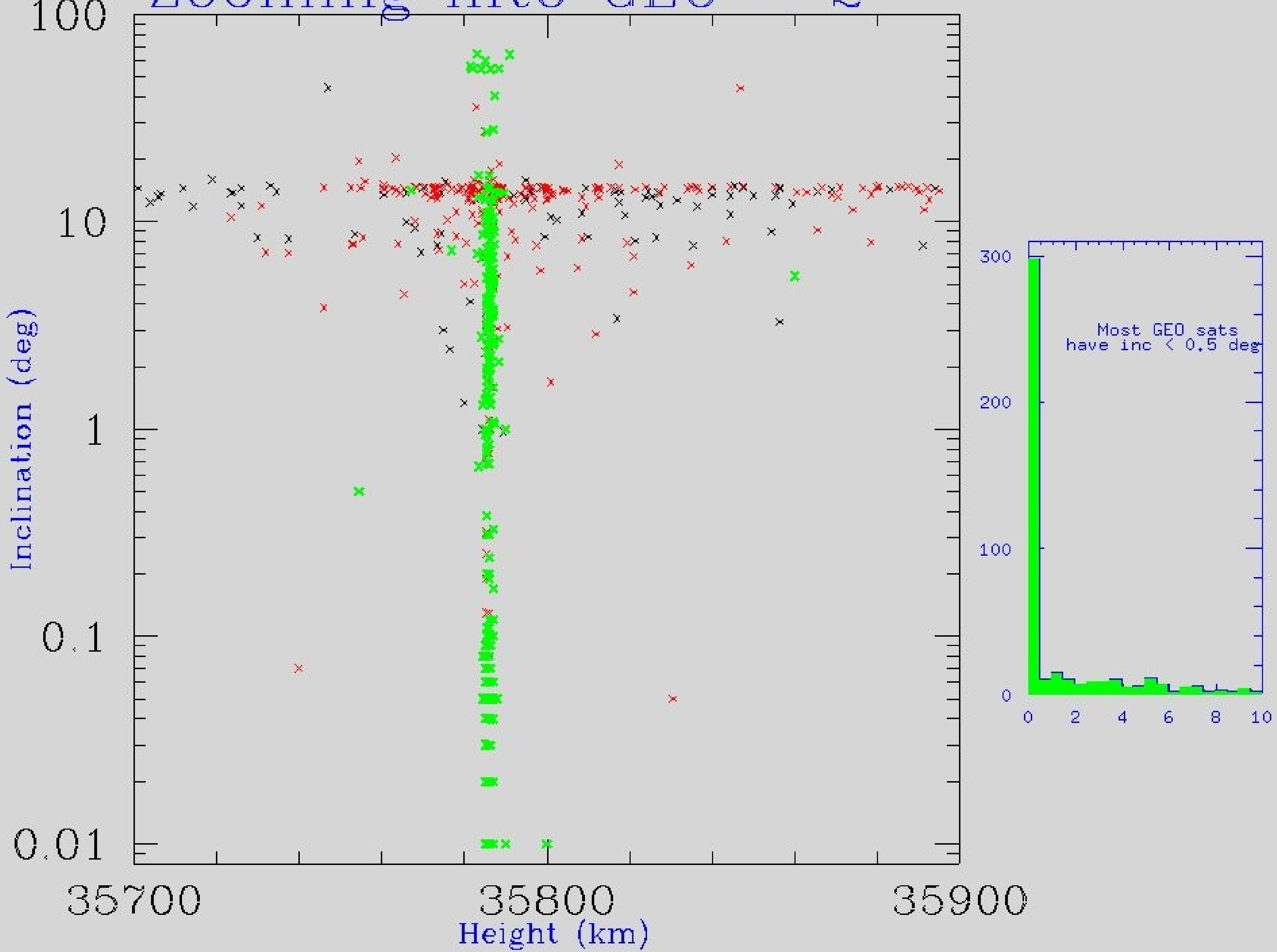
Green:
Steady growth of communications sector





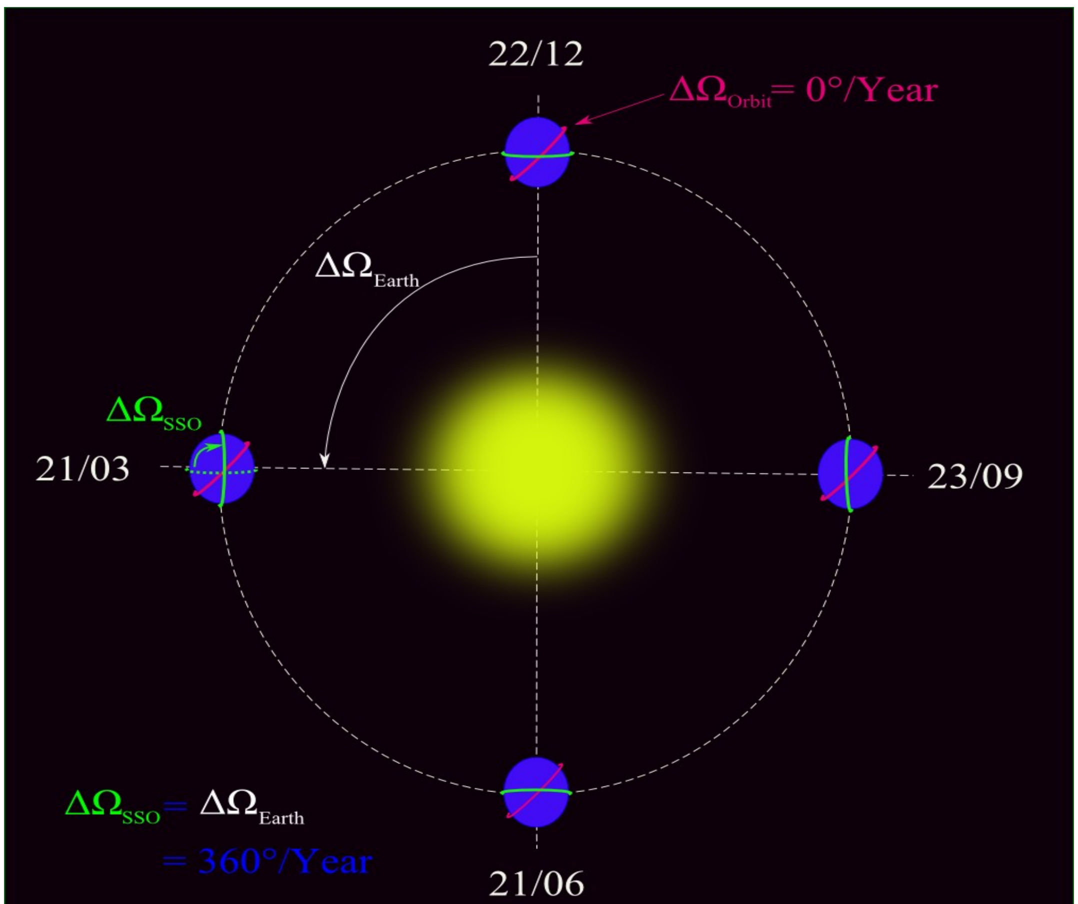
A Map Of Earth Orbit
Active
Dead
Junk
Inclination (deg)
150
100
50
0
100
1000
10^4
10^5
10^6
Height (km)
SSO
ISS
GPS
GEO
Moon
Retrograde
Polar
Equatorial

Zooming into GEO - 2



SSO: Sun Synchronous Orbit

Actually we left something out of our math: the Earth is NOT ROUND!
It's a little squashed at the poles (polar radius is 22 km smaller than at equator)
Every time a sat goes over the poles, it gets less of a tug; over the equator it gets more.
This twists the orbit – makes it rotate in space.
We consider the first term (J2) in the spherical harmonic expansion of the potential
This gives first order corrections to the orbital elements (node, arg of peri.)
- varying linearly in time
By picking the orbit cleverly you can make the twist do something useful.



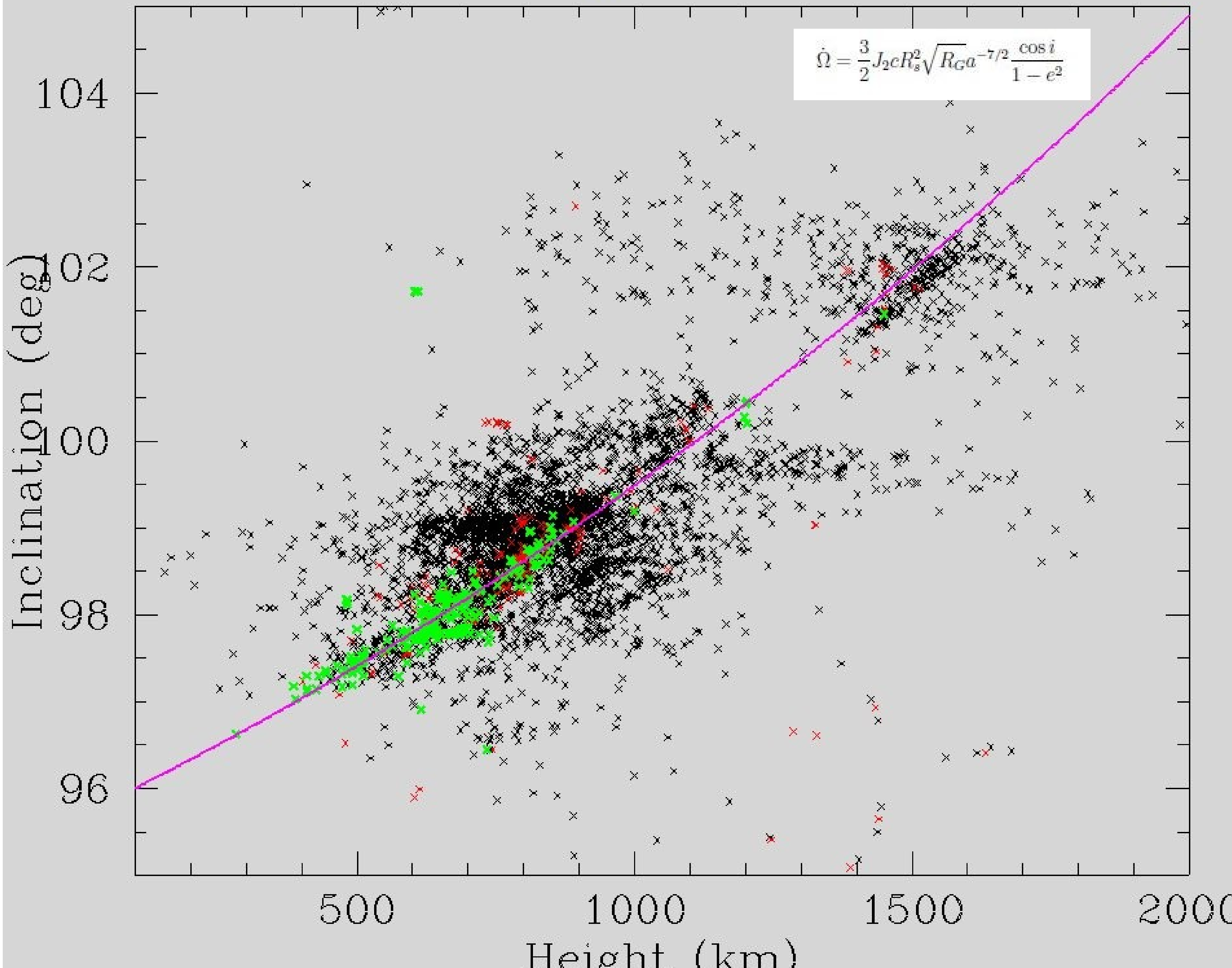
Source: wikipedia

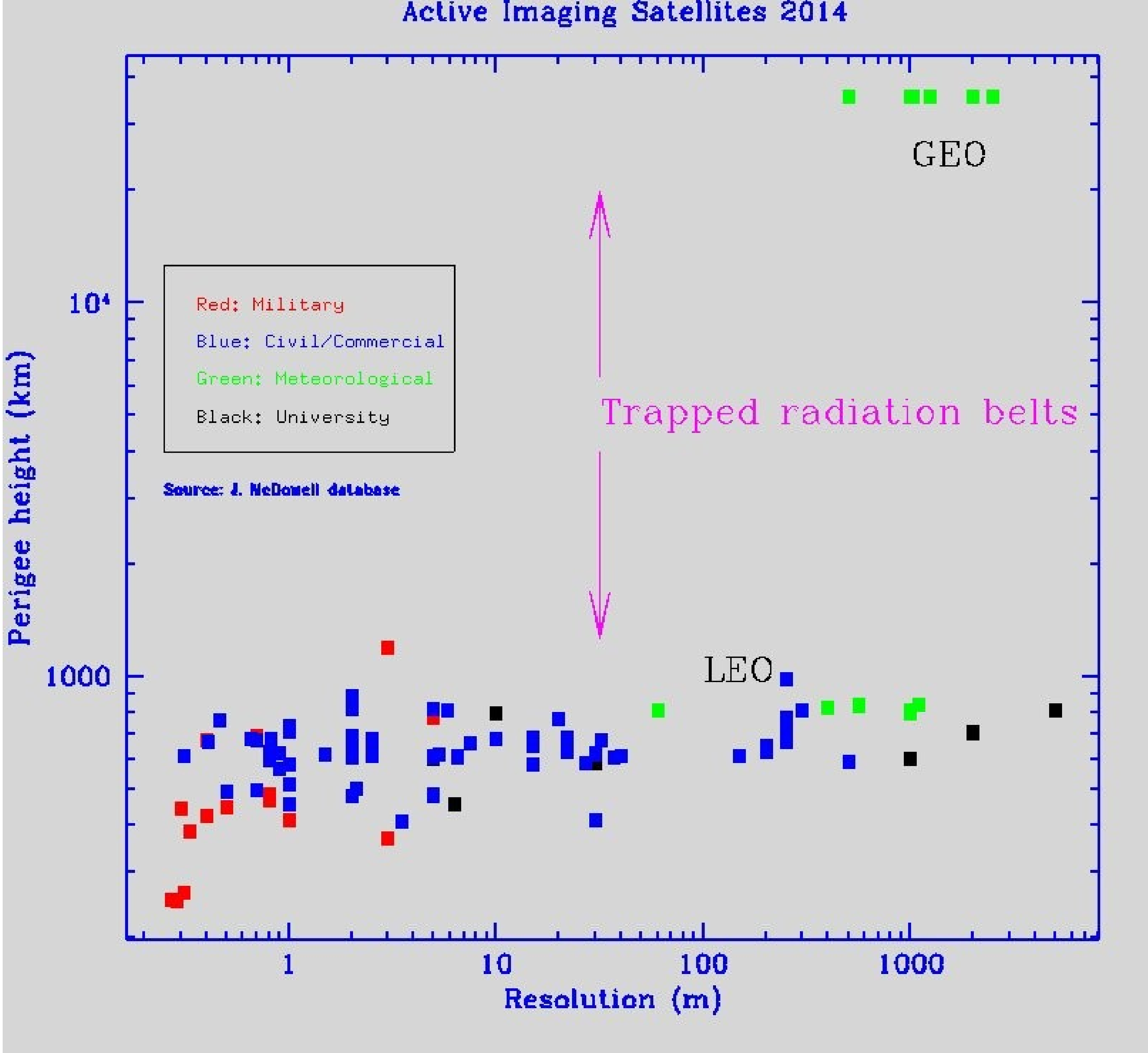
The magenta colored orbit is what you get for a perfect sphere Earth

It stays fixed in space so in August (in this particular case) it is facing the sun – the satellite orbits over the dawn/dusk line
- but in May the orbit is edge on to the sun, orbiting noon to midnight.

The green colored orbit is SSO, turning so it's always facing the Sun

Zooming into SSO





Total:
161 sats

IMAGING SATELLITE LIMITATIONS

Ground resolved distance vs. swath (image width in km)

- Traditionally, large swath, low resolution, high altitude (e.g. weather sats)
  small(er) swath, high res, low altitude (spy sats)

Latency vs bandwidth

- How much data per day?
- How soon do you get the data?

Old film return spy sats: high bandwidth, very low latency

You can get a LOT of megabyte-equivalents in a film canister but you have to wait weeks or months to get it...

Modern imaging satellites:

Spy satellites use GEO data relay sats for immediate availability of raw data
Civilian satellites use ground stations – latency of a few hours to days, and limited time (=> bandwidth) to download during a pass

Additional latency for ground software to process raw telemetry to processed, value-added data products often dominates

Low Earth Orbit

- a brief polemical digression

Earth surface has $R = 6378$ km and $R_G = 4.4$ mm
ISS has height h = 400 km so $r = R + h = 6778$ km
Then

$$\sqrt{R_G/r} = 1/39250$$

corresponding to v = 7.67km/s = 17158mph and orbital period T of 92.5 min.

The constant 'big G' is evil and has confusing units. By using

$$R_G = \frac{GM}{c^2}$$

instead we make the dimensionality more obvious as well as easily seeing how far we are from being in the GR limit:
Consider orbits around an object of mass M, radius R_s and gravitational radius R_G (where we will consider only the case $R_s \gg R_G$!). From Newton's law of gravitation, the potential is

$$V = mc^2 \left(\frac{r}{R_G}\right)^{-1}$$

it follows trivially that circular orbits of radius r will have

$$v/c = \sqrt{R_G/r}$$

The orbital period T is then given by

$$T = \frac{2\pi r}{c}\sqrt{r/R_G}$$

In other words, the orbital period is
the time it would take to go round the orbit at the speed of light
times root of
the ratio of the orbit size to the size of an Earth-mass black hole.
This is Kepler's third law.

Now consider an imaging satellite orbiting at height h
with angular field of view α resulting in a nadir swath width

$$s = h\alpha$$

In time t the satellite will see an area $A = svt$
so for typical LEO values and s ~ 100 km, A~ 3 million sq km / hr

In one orbit you see $2\pi Rs$ (where R is Earth radius)
In LEO, the next orbit crosses the equator ~22 deg W of the previous one because of Earth rotation, which given actual values of s for current satellites means that the swaths do not overlap there..

so it takes you $N = 4\pi R^2/2\pi Rs = 2R/s$ orbits to cover the surface area of the Earth
- *except of course that the swaths overlap at the poles, we will neglect that.*

The fraction of the Earth's surface seen in unit time is

$$f = (csR_G^{0.5}/4\pi R)(R+h)^{-1.5} = 0.11\,(s/100\text{ km})(1+h/6378\text{ km})^{-1.5}\text{ per day}$$

… *if only the satellite had high def video streaming* (which they don't)
… *if only they could see in the dark* (I am considering visible light imagers, not radar satellites)

In fact the observing efficiency relative to this calculation can be about 10 %.

Largest US commercial imagery operator: DigitalGlobe

5 main satellites:

	Resolution m	Swath km	Orbit ht km	f	eff %	coverage mplanet/d
Ikonos	0.82	11.3	681	0.010	5	0.47
GeoEye-1	0.41	15.2	671	0.014	5	0.68
WorldView-1	0.50	17.6	496	0.017	9	1.47
WorldView-2	0.46	16.4	764	0.015	13	1.91
WorldView-3	0.31	13.1	617	0.012	11	1.33

Total capacity 3 million sq km / day
Compare Earth surface area: 511 million sq km
So a constellation of 5 top-end satellites covers 6 milliplanets per day
Would need 4000 such satellites for hourly global coverage
How many are there?

Sources: DigitalGlobe (actual claimed coverage)
Herb Kramer/eoportal.org (sensor parameters)
USAF/space-track.org (orbit data)

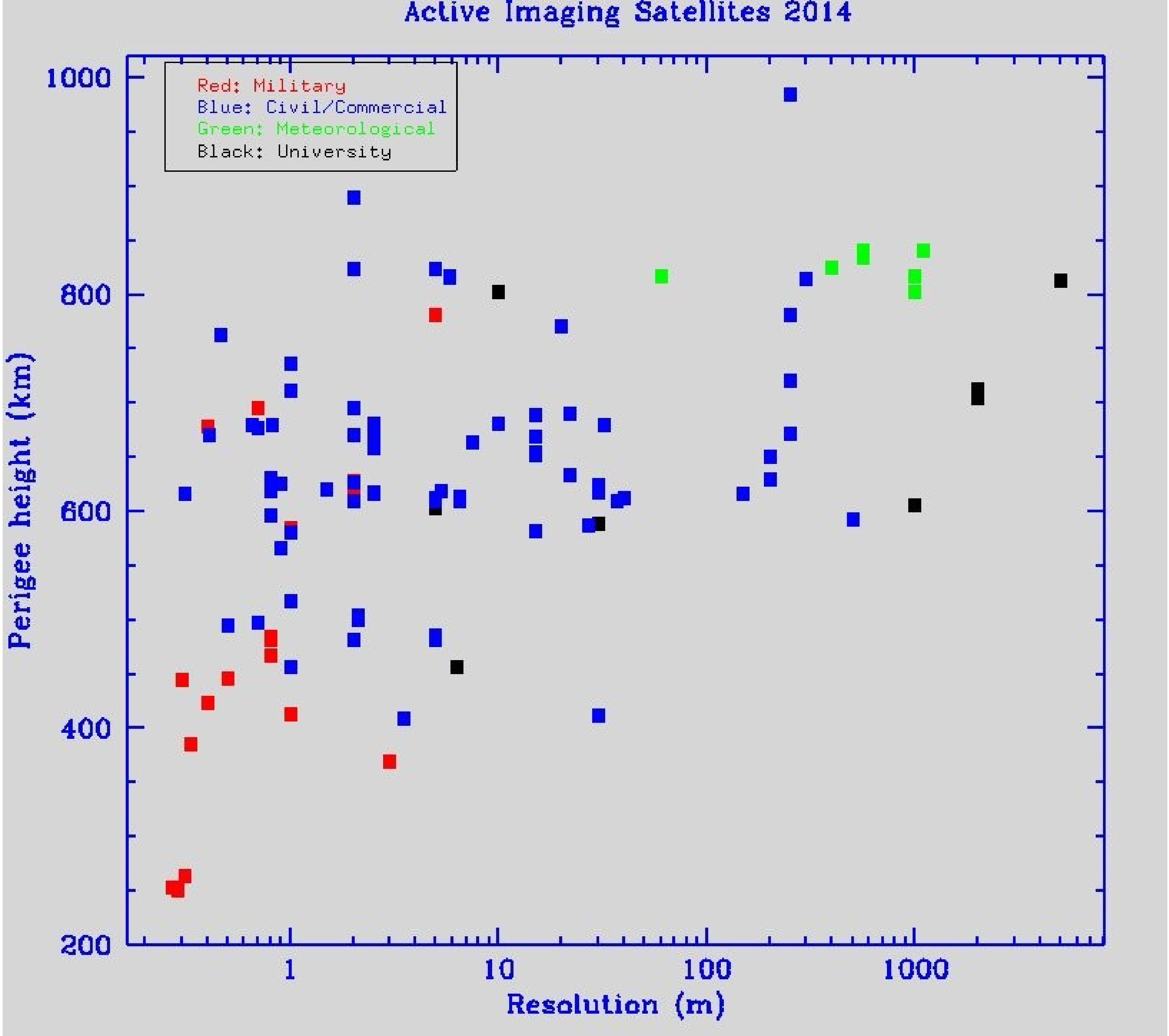
WV-1

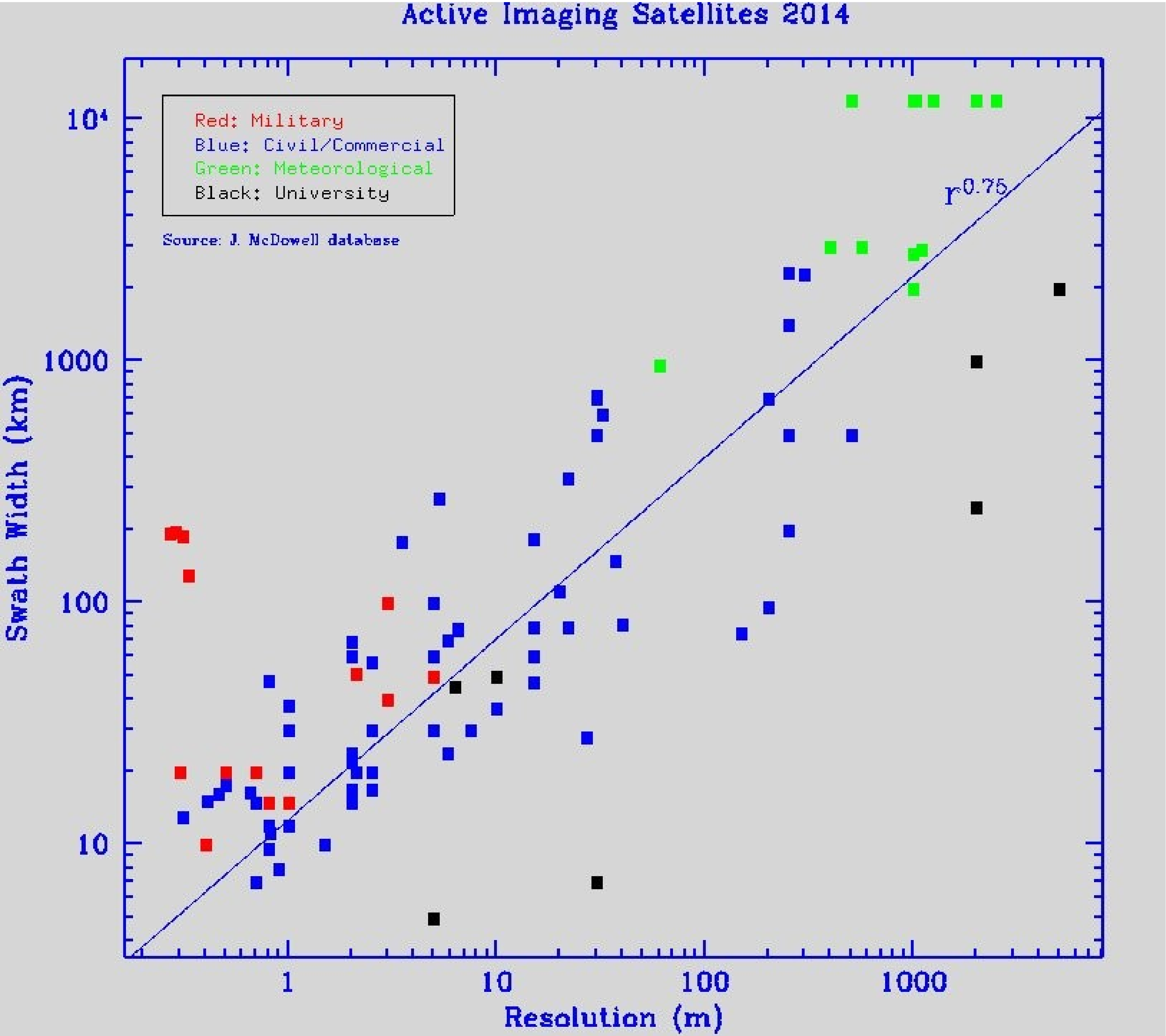
WV-2

WV-3

Ikonos

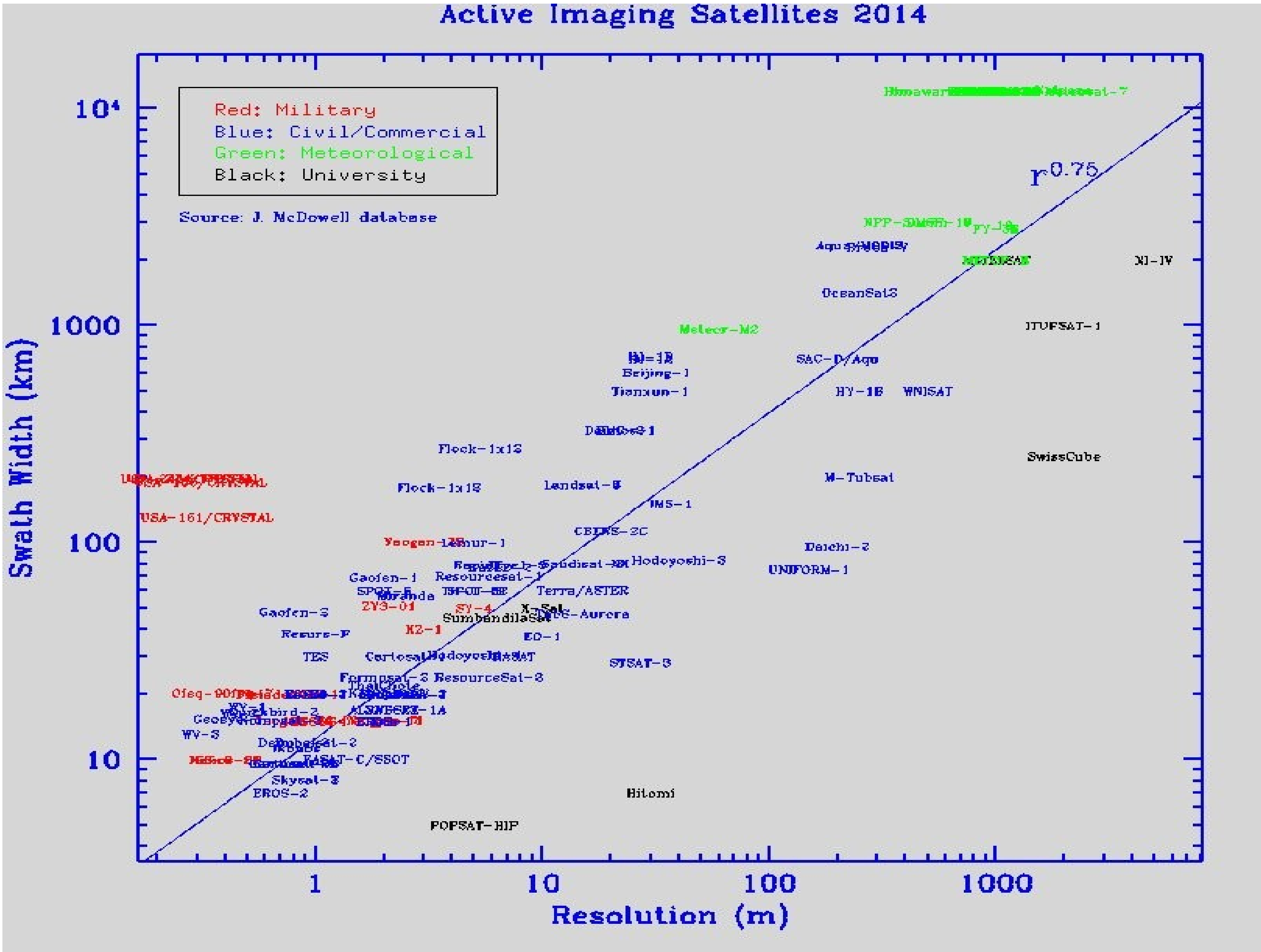
GeoEye-1


Active Imaging Satellites 2014
Red: Military
Blue: Civil/Commercial
Green: Meteorological
Black: University
Perigee height (km)
1000
800
600
400
200
1
10
100
1000
Resolution (m)

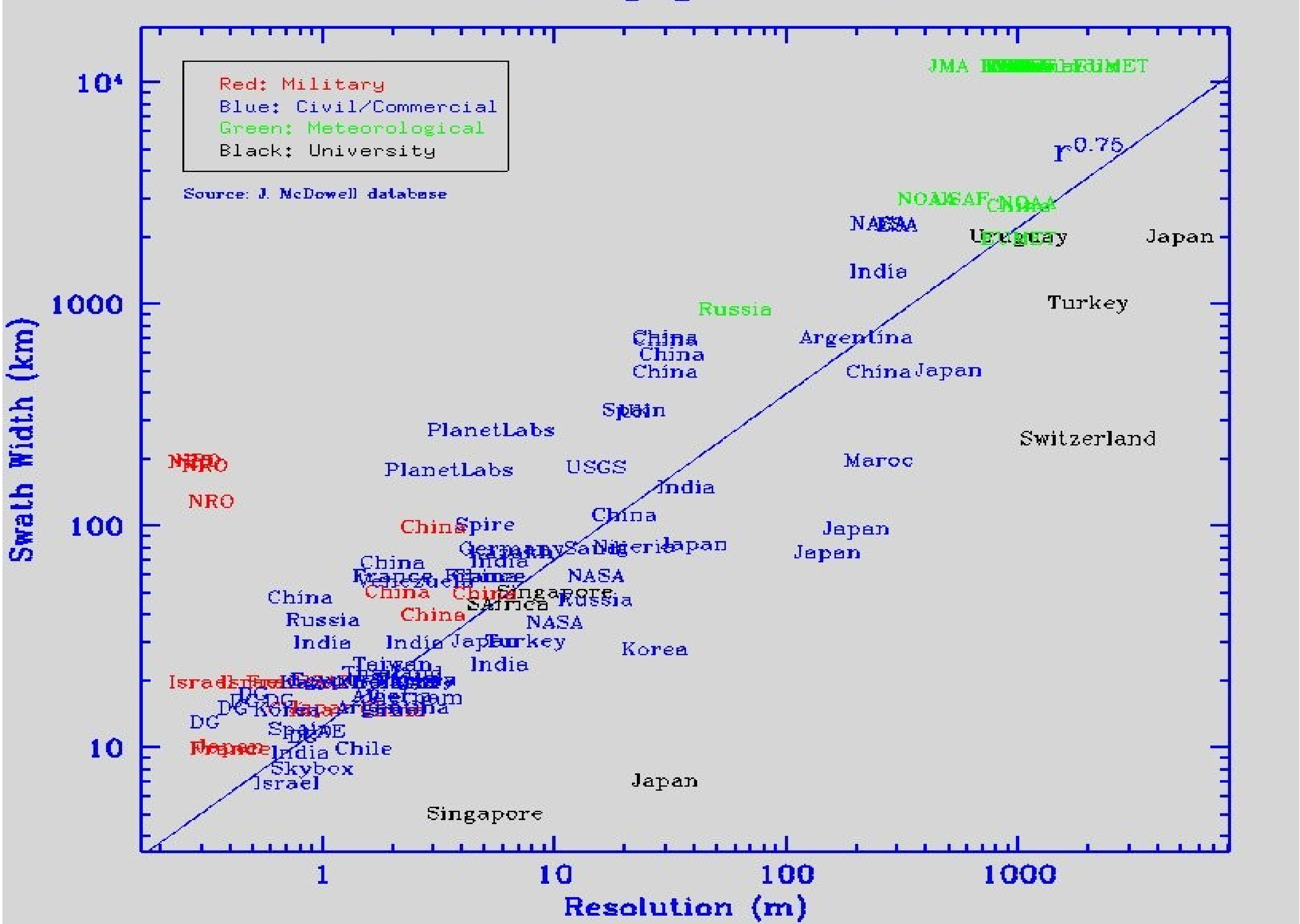


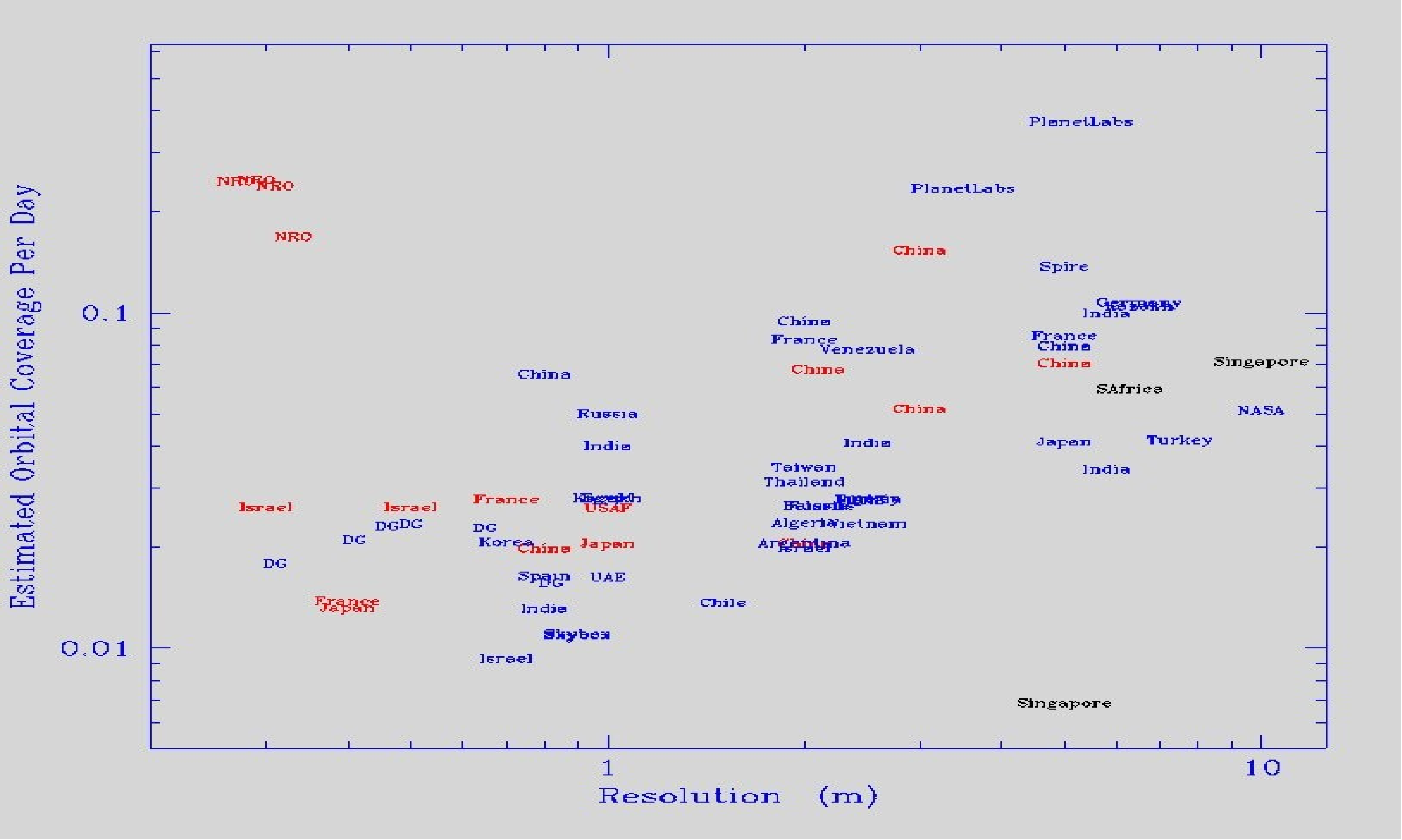
Active Earth visible-light imaging satellites: 161

With resolution <= 10m: 100


Active Imaging Satellites 2014
Red: Military
Blue: Civil/Commercial
Green: Meteorological
Black: University
Source: J. McDowell database
r^0.75
Swath Width (km)
Resolution (m)
10^4
1000
100
10
1
10
100
1000
Meteor-M2
OceanSat3
SAC-D/Aqu
HY-1B
WNISAT
Beijing-1
Tianxun-1
Flock-1x12
Flock-1x18
Landsat-8
M-Tubsat
NI-IV
ITUPSAT-1
SwissCube
USA-161/CRYSTAL
CBERS-2C
Daichi-2
Hodoyoshi-3
UNIFORM-1
Gaofen-1
Resourcesat-1
Terra/ASTER
Gaofen-2
ZY3-01
SY-4
X-Sat
SumbandilaSat
Resurs-P
KZ-1
EO-1
TES
STSAT-3
Formosat-2
ResourceSat-2
WV-3
FASAT-C/SSOT
Skysat-2
EROS-2
Hitomi
POPSAT-HIP

Active Imaging Satellites 2014





When corrected for estimated 10% efficiency,
total coverage is 0.44 planet/day (0.19 from spy sats, incl. 0.09 from NRO alone)
Of this, 0.16 is from high res (<1 m) satellites.
Note: Spy satellite swaths and efficiencies uncertain by factor 2 or so

CONCLUSIONS

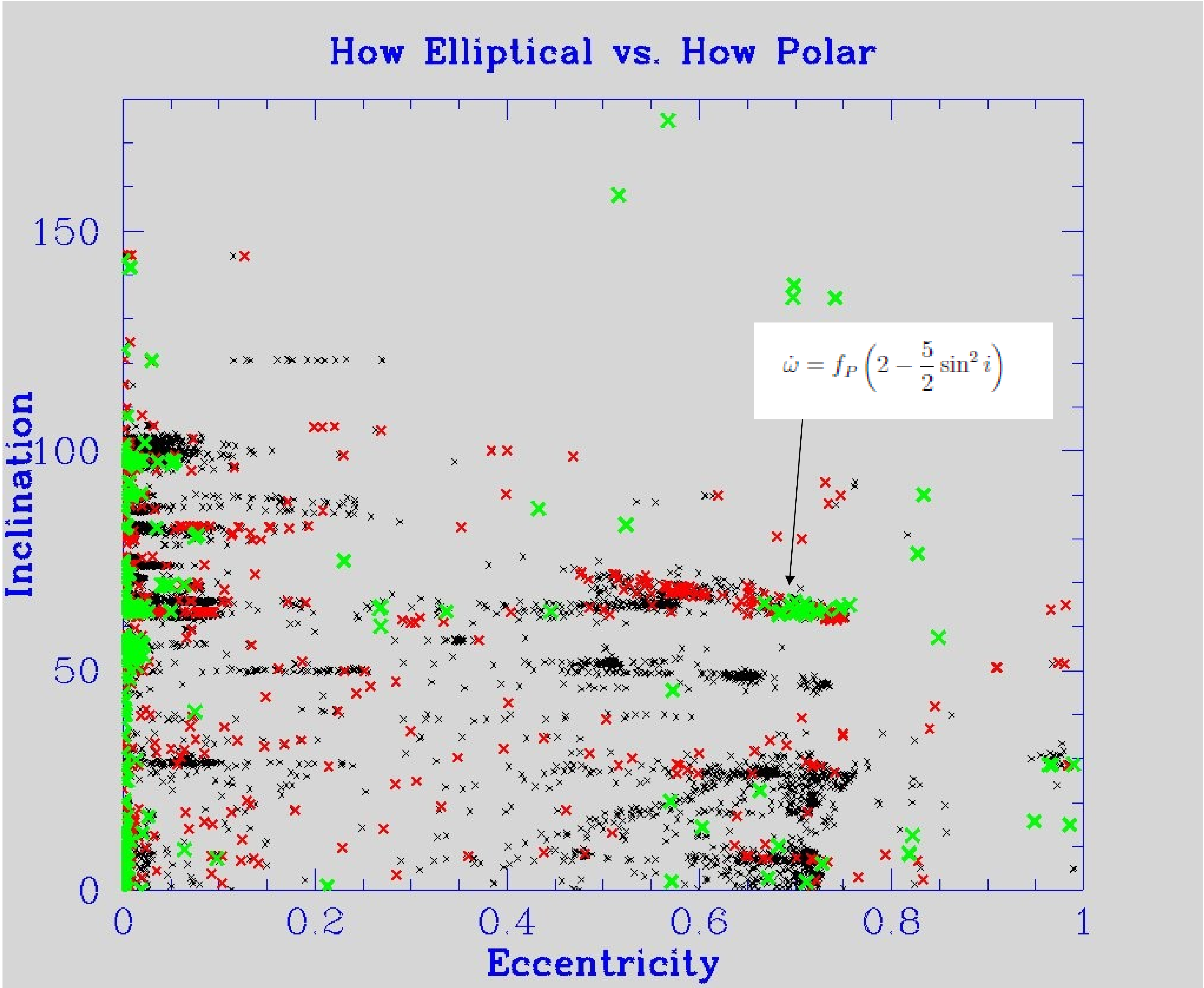
Imaging spy satellites are watching us – but not ALL the time. Yet.

The real near-ubiquitous surveillance is more subtle: communications satellite technology provides a hidden infrastructure that can be used in surprising ways

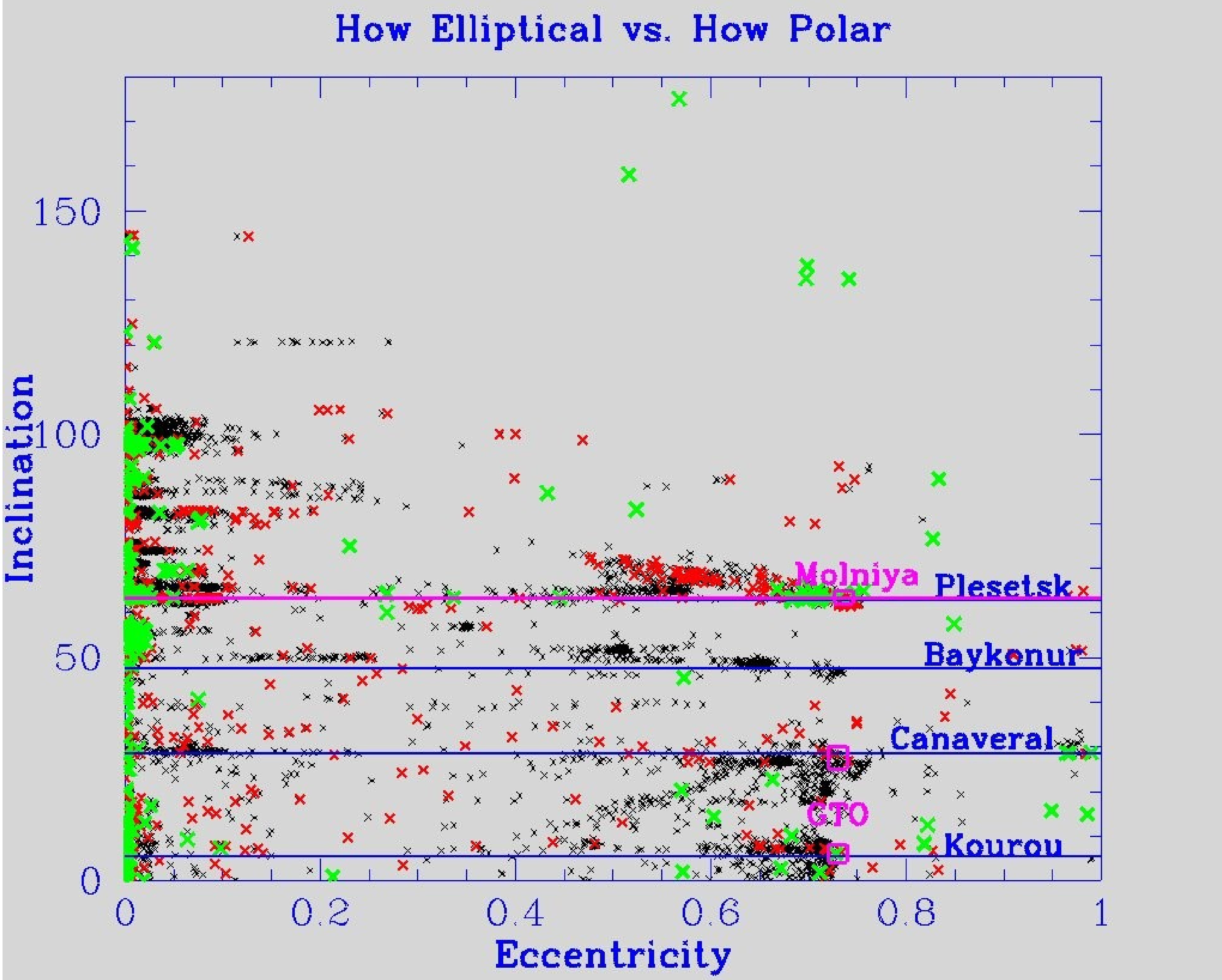
We still don't know what happened to MH370, but time-delay and Doppler evidence hidden in network communications metadata allow its location to be constrained.

Increased, cheaper satellite broadband capacity will allow us to stream internet video in coach class – this and deployment of space-based ADS-B will ensure airliners stay in touch with data centers during transoceanic flights.

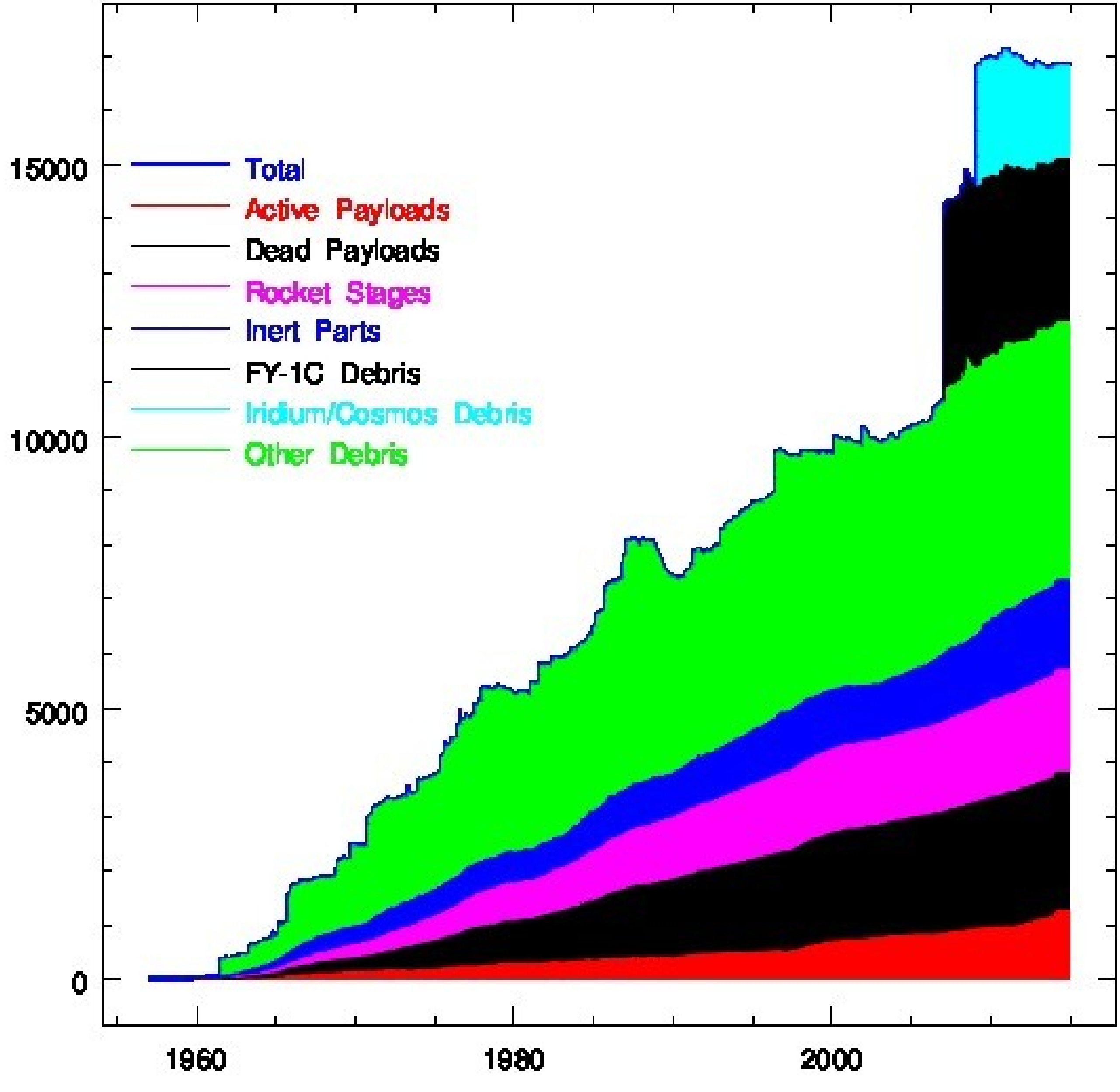
More fun with orbit databases



How Elliptical vs. How Polar
Inclination
Eccentricity
0
50
100
150
0
0.2
0.4
0.6
0.8
1
$\dot{\omega} = f_P\left(2 - \frac{5}{2}\sin^2 i\right)$


How Elliptical vs. How Polar
Inclination
Eccentricity
0
50
100
150
0
0.2
0.4
0.6
0.8
1
Molniya
Plesetsk
Baykonur
Canaveral
GTO
Kourou

The Growth of Space Junk



Space Junk - mass in metric tons