Measuring our galaxy and beyond

William O'Mullane, AURA/LSST
DM Project Manager

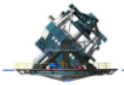
18th July 2018 Scoil Mhuire, Clontibret, Monaghan, Ireland

Early background

- 1982-87 High School in Fethard Co. Tipperary
- 1984ish started with BASIC on a Commodore (still kept horses)
- 1987-93 MSc BSc Computer Science, University College Cork, Ireland
- 1993 iESA Young Graduate Trainee - ESOC Germany.
- 1994-97 Spacecraft Control Systems (C++), ESA ESOC Germany
- 1997-2001 Hipparcos, Integral, Planck, Gaia, Bepi-Sax (C,Java,Oracle, HTM, HEALPix), ESA ESTEC Netherlands
- 2012 PhD in Physics on Implementing the Gaia Astrometric Solution, Barcelona University

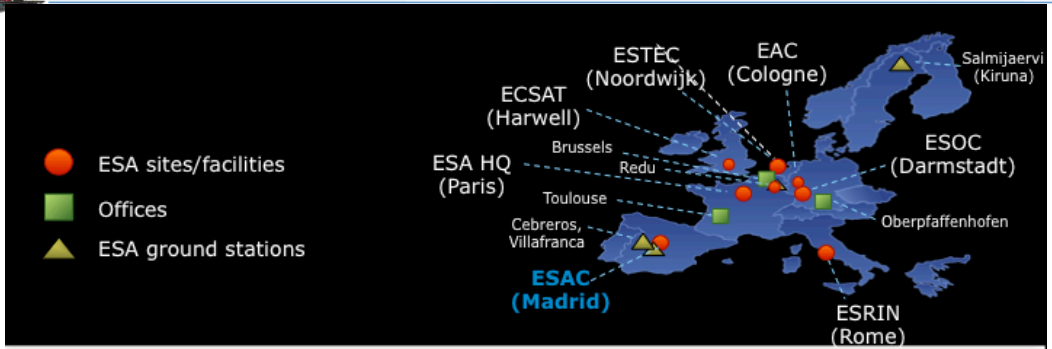
YGT is still running - "about 100 YGT job offers, aimed mainly at engineers and physicists, graduates in Information Technology, Natural or Social Science and Business"
`https://www.esa.int/About_Us/Careers_at_ESA/Graduates_Young_Graduate_Trainees`

South of Spain



Outline of the talk

European Space Agency



Late 1990s SCOSII software contractors

- ESOC - Located in Darmstadt, near Frankfurt, Germany.
- Controls all ESA satellites.
- System design/engineering, requirements management, advanced studies ..
- SCOSII (Satellite Control and Operations System) for ENVISAT

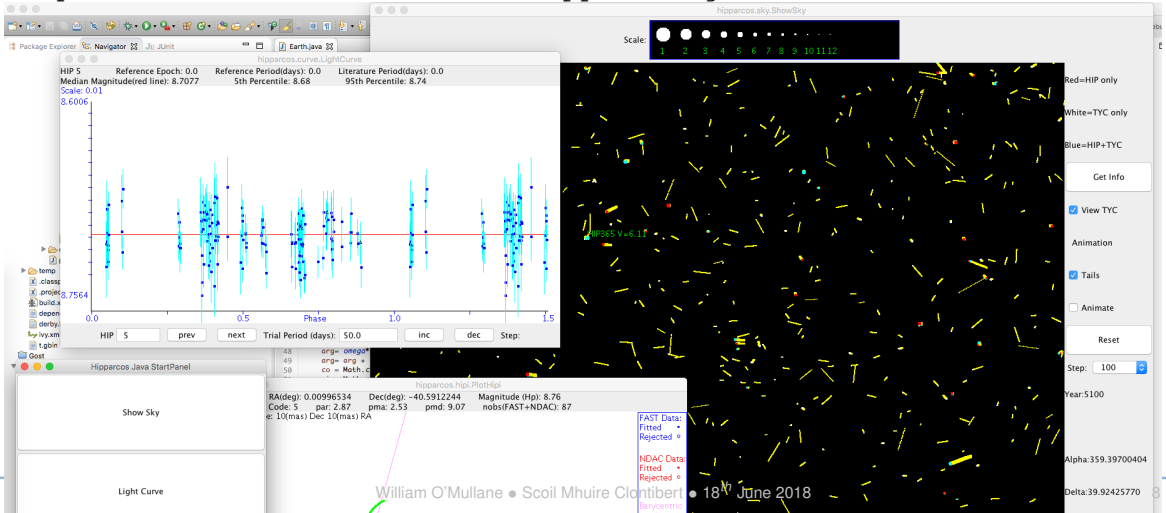
1998 Integral in ESTEC

- ESTEC - Located near Noordwijk, Netherlands.
- Worked on Hipparcos, Integral, Planck and Gaia study phase:
  - First ideas on Global Astrometric Solution (O'Mullane & Lindegren, 1999) and how to make a consortium.
  - How to tesselate the celestial sphere : HEALPix and HTM work proved popular (O'Mullane et al., 2001).

Addition to HIP Catalogue

1997/98 Hipparcos Java Tools - learning Astrometry

http://www.cosmos.esa.int/web/hipparcos/java-tools

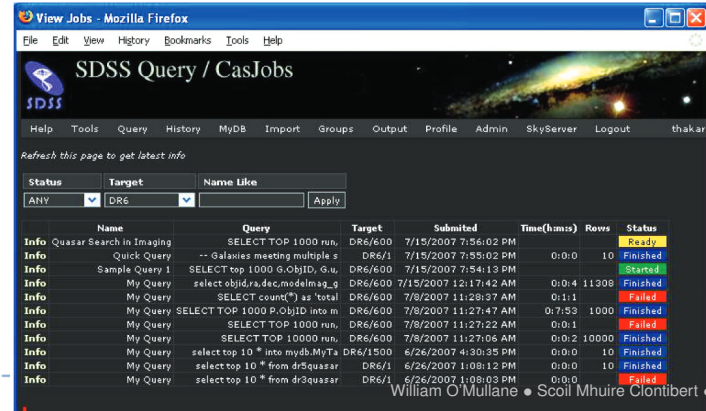


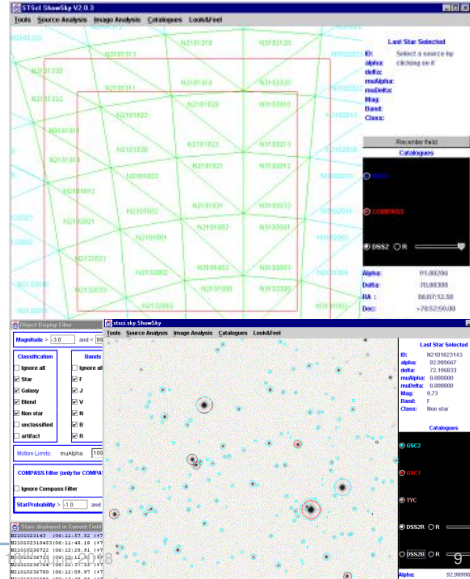
In the USA early 2000s

Entering the new millennium ..

Quality tools for GSC2 (Java) →

CasJobs (C#)(O'Mullane et al., 2004)

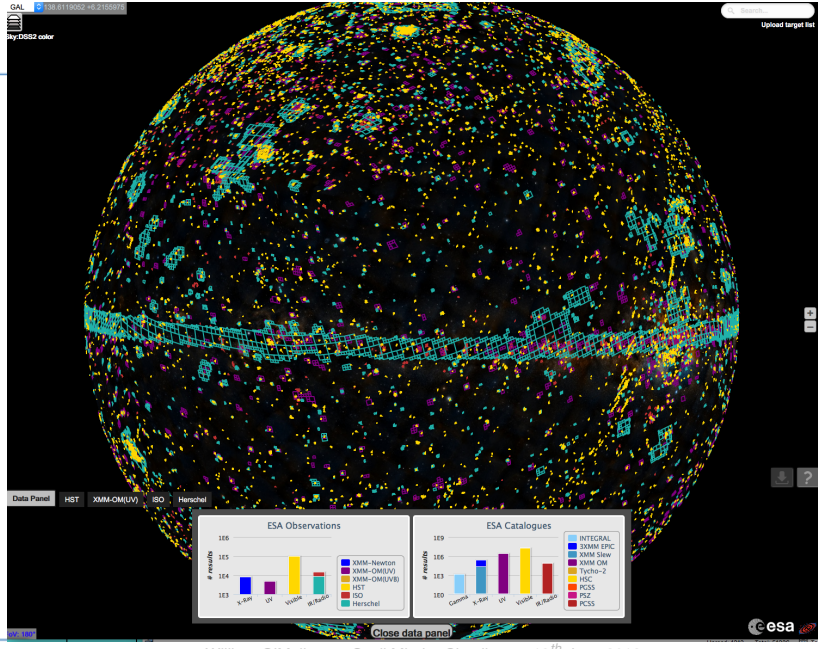




European Space Astronomy Centre

From 2005 to 2017

- ESAC Located near Madrid, Spain.
- Home of the Science Operations Department of the Eurpoean Space Agency
- Surprising number of Irish people ..
- This picture from a public stargaxing night - $\sim$400 visitors came


GAL
Sky:DSS2 color
Upload target list
Data Panel
HST
XMM-OM(UV)
ISO
Herschel
ESA Observations
results
X-Ray
UV
Visible
IR/Radio
XMM-Newton
XMM-OM(UV)
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ESA Catalogues
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INTEGRAL
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XMM Slew
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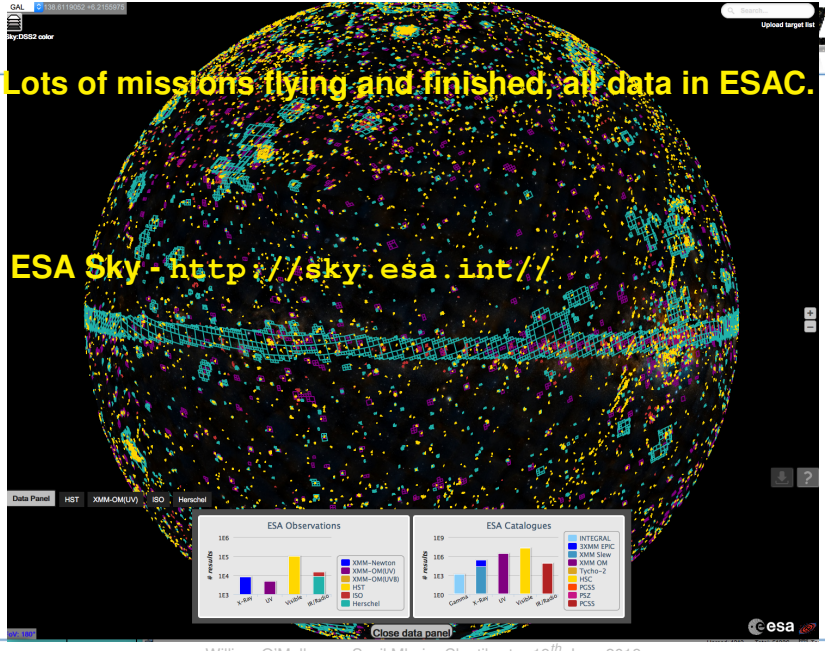
Tycho-2
HSC
PGSS
PSZ
PCSS
Close data panel
esa


Lots of missions flying and finished, all data in ESAC.
ESA Sky - http://sky.esa.int/
Sky:DSS2 color
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ISO
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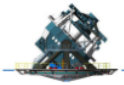

Outline of the talk


Milky way analogue NGC1232
‘Our sun’→
Jos de Bruijne

Milky way analogue NGC1232

‘Our sun’→

Our view is severely obstructed by the dust in the disk and relatively little is known about the origin, history, and structure of our own Galaxy

Gaia’s main aim: unravel the formation, composition, and evolution of the Galaxy

Some numbers and scales

- **K**ilo = 1000 = 10^3 **M**ega = 1000000 = 10^6 **G**iga = 1000000000 = 10^9 **T**era = 10^{12}
- But note in computing .. KB = 1024 Bytes .. 2^{10}

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- 1 AU (astronomical unit) distance of earth from sun $\sim 1.49610^{11}$ Meters
- 1 light year $\sim 9.461 \times 10^{15}$ Meters sin63241 AU

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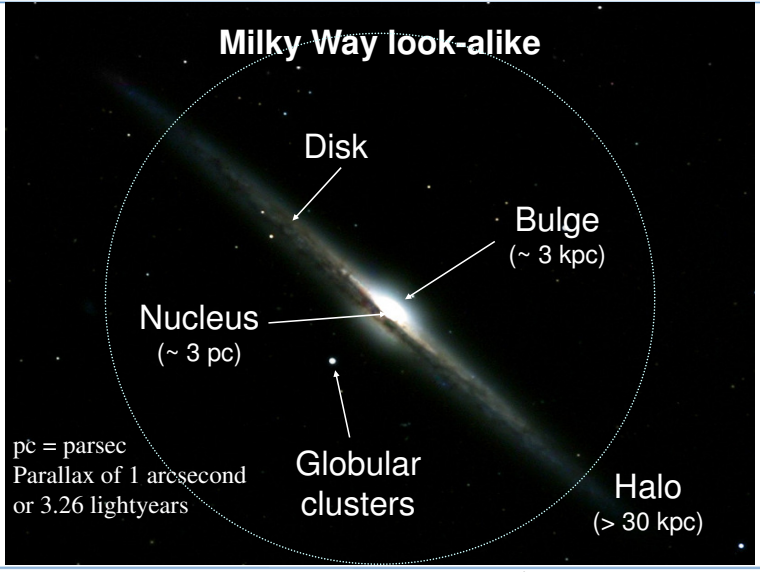
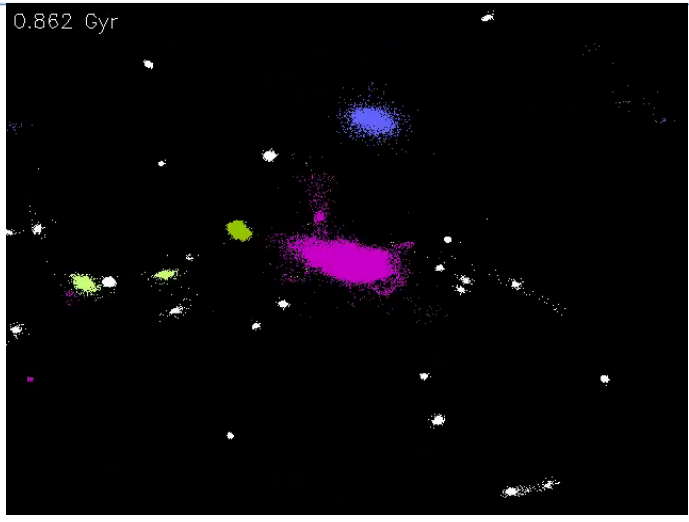
- Parallax of $1''$ known as 1 parsec $\sim$ 3.26 Light years $\sim$ 206165AU
- 3.26light years $= 3.26 \times 9.461 \times 10^{15} \sim 3.084 \times 10^{16}$Meters

Another Milky way Analogue (NGC4565)



Origin of the Milky Way



Movie credit: Amina Helmi, University of Groningen

slides from Anthony Brown, Leiden University

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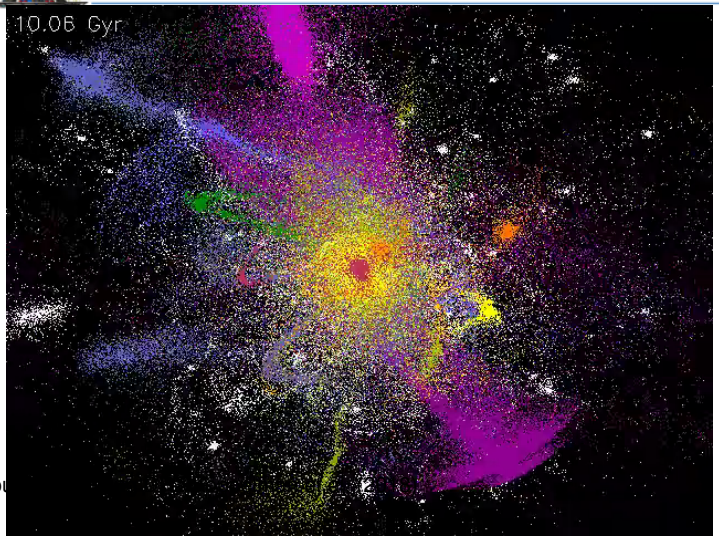
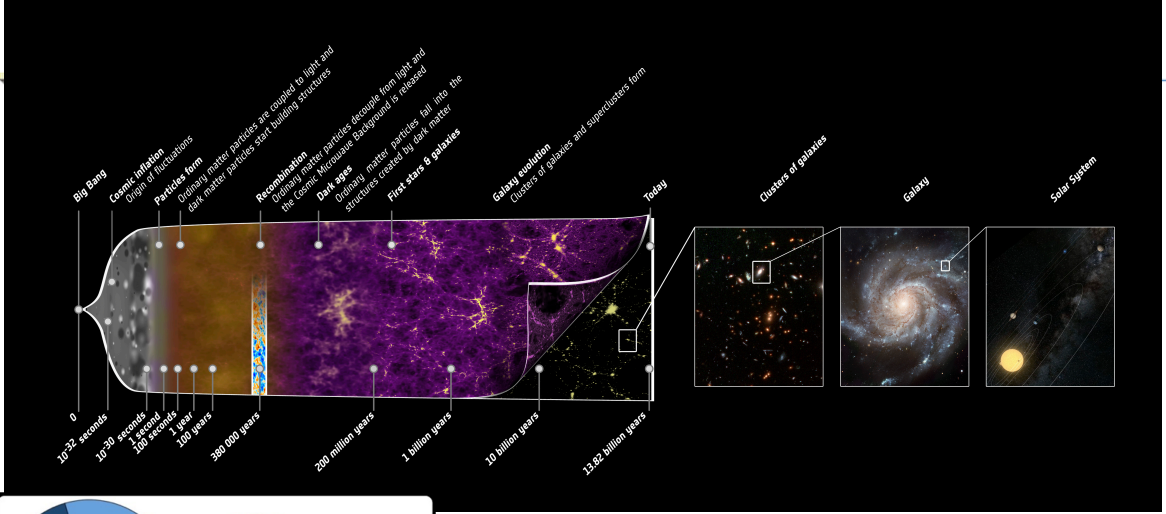
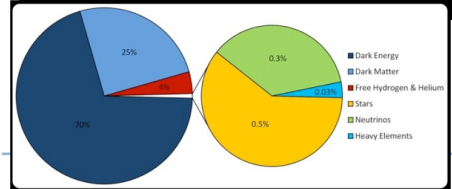
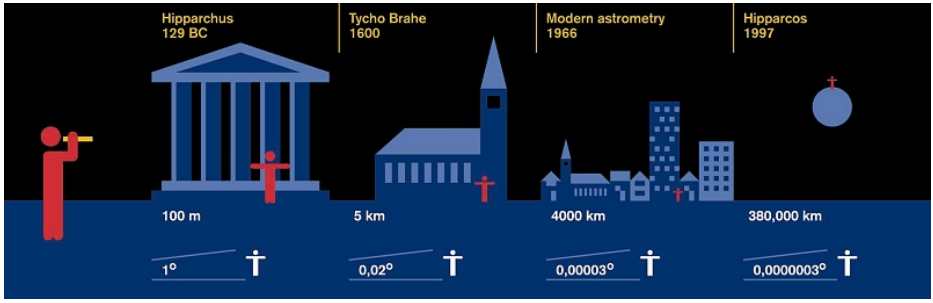


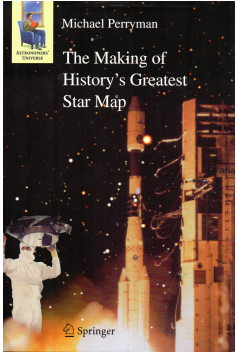




The modern cosmological models can explain all observations, but need to *postulate* dark matter and dark energy (though gravity model could be wrong, too)

Hipparchus to ESA's Hipparcos





Gaia will take us to the next order of magnitude the microarcsecond.
e.g. A euro coin on the moon viewed from earth

Hipparcos measured 10^5 objects : Gaia measures 10^9

← superb account of the Hipparcos mission.

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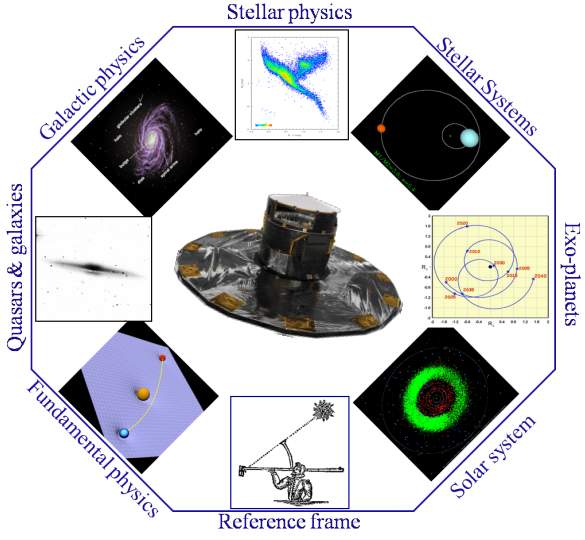
Science topics



Killer asteroids: the impact probability is not 0!

LSST is the only survey capable of delivering completeness specified in the 2005 USA Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)

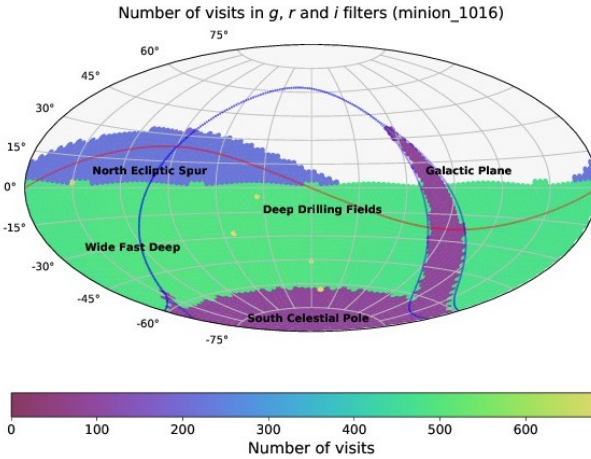
The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

LSST:uniform sky survey

An optical/near-IR survey of half the sky in ugrizy bands to r 27.5 (36 nJy) based on 825 visits over a 10-year period: *deep wide fast*.

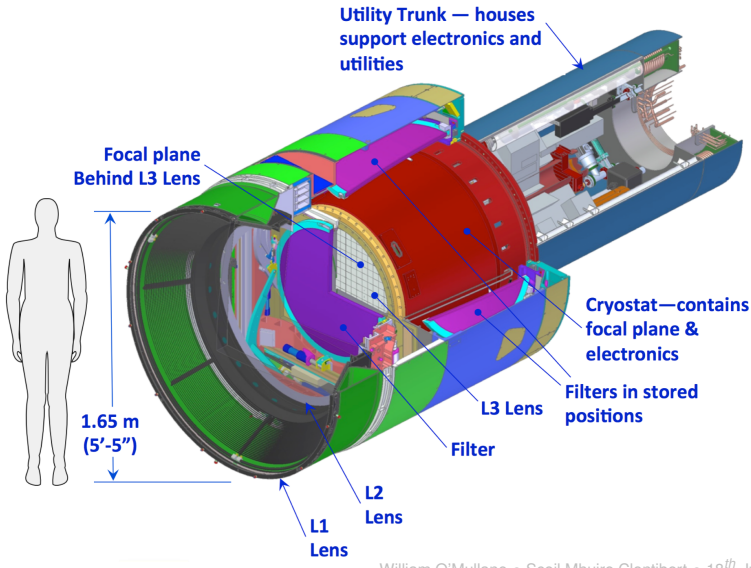
- 90% of time spent on uniform survey: every 3-4 nights, the whole observable sky scanned twice per night
- 100 PB of data: about a billion 16 Mpix images, enabling measurements for 40 billion objects!

see also `http://www.lsst.org` and Ivezic et al. (2008)-arXiv:0805.2366



10-year simulation of LSST survey: number of visits in u,g,r band (Aitoff projection of eq. coordinates)

LSST Camera



The largest astronomical camera:

- 2800 kg
- 3.2 Gpix

Site shaping up

Data management

DM Mission :
Stand up operable, maintainable, quality services to deliver high-quality LSST data products for science, all on time and within reasonable cost.

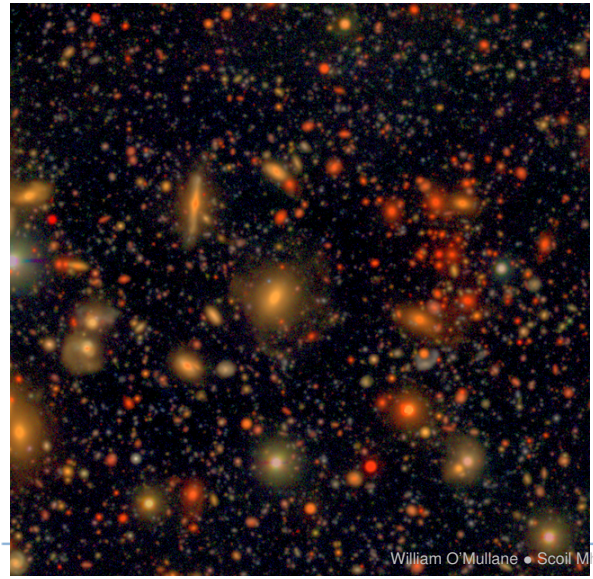
LSST DM development is distributed across the Americas.
Plus we have partners like IN2P3

SDSS image

Nice colours Lupton et al. (2004)
$\approx 3.5'$

Image Robert Lupton

Hyper Suprime Cam (HSC) on Subaru

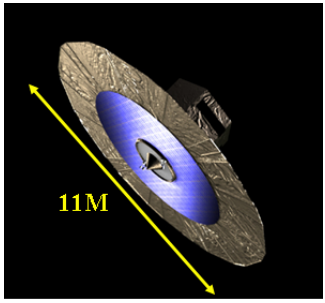


HSC image (COSMOS) from g,r(1.5 hrs) ,i(3 hrs) PSF matched co-add ($\approx$ 27.5)

Processed with *LSST Stack*
`https://pipelines.lsst.io/`

Image HSC collaboration, Robert Lupton

Satellite overview



– Mission:
  - ESA Corner Stone 6
    - ESA provided the hardware and launch
      Mass: 2120 kg (payload 743 kg)
      Power: 1631 W (payload 815 W)
  - Launched December 19th 2013
  - Stereoscopic Census of Galaxy over 5 years
    - Possible extension of 1 year - have fuel for at least that
  - μarcsec Astrometry $G < 20$ (10^9 sources)
  - Radial Velocities $G < 16$
  - Photometry millimag $G < 20$

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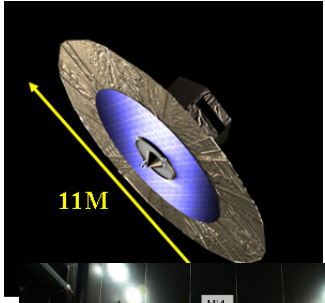
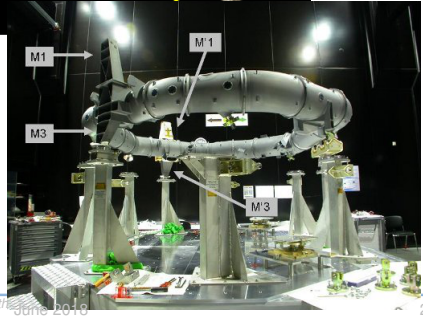
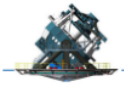
- Final catalogue $\approx$ 2022







Outline of the talk

To Kourou

Lots of interesting signs ..

Up close

Dec 18th saw (touched) our Fregat.
Meanwhile a full dress rehearsal ongoing.
Later road closed for Ariane movement

Countdown..

Dec 18th 17:12 (20:12 UTC) the count down started. In Jupiter control room

Flawless lift off 19/12 06:12am

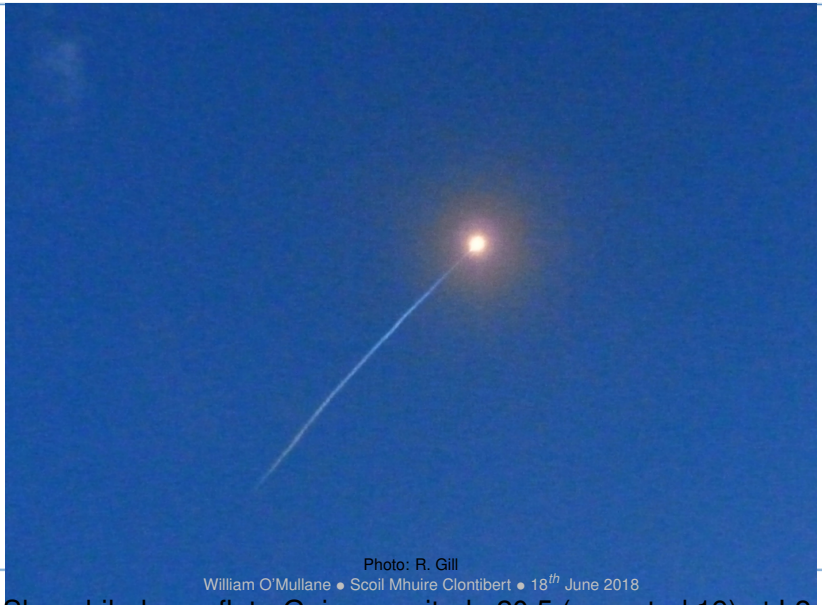
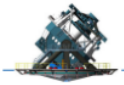


Photo: R. Gill

Video clips

- Gaia Launch `https://youtu.be/xDmQvJVJg8Y?t=87`
- Gaia Data Release 2 `https://youtu.be/KULtrwVSq6g?t=10`
- Cerro Pachon LSST
  `https://gallery.lsst.org/bp/#/folder/2689925/64565141`



Outline of the talk

Just one part of the Gaia processing !
From the Hipparcos catalogue (ESA, 1997, Volume 3 Chapter 23).

Minimisation problem for astrometry

$$\min_{\mathbf{a},\mathbf{n}} \|\mathbf{g}^{\mathbf{obs}} - \mathbf{g}^{\mathbf{calc}}(\mathbf{a},\mathbf{n})\|_M \quad (1)$$

- $\mathbf{a}$ is the vector of unknowns describing a star's barycentric motion represented by the measurement vector $\mathbf{g_k} = (G_k, H_k)'$ and associated statistics.
- $\mathbf{g}^{\mathbf{obs}}$ represents the vector of all measurements
- $\mathbf{g}^{\mathbf{calc}}$ represents the vector of detector coordinates calculated from the astrometric parameters.
- $\mathbf{n}$ is a vector of nuisance parameters - required for realistic modeling (e.g. attitude, instrument calibration)
- M metric defined by the statistics of the data, (error weighting)

The complete new formulation for Gaia is in (Lindegren et al., 2012).

Basic Gaia Problem

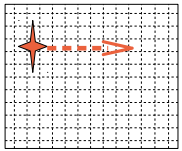
Put more simply the data reduction must:

find the astrometric parameters (catalogue) best predicting the (10^{12}) focal plane observations of the sources. (O'Mullane et al., 2011)

Catalogue Data

ID	α	δ	ϖ	μ_α	μ_δ	μ_r
...						
0000101	1.4	3.1	0.1	0.02	0.02	-
....						
1001000	2.7	1.2	0.2	0.05	0.01	0.01

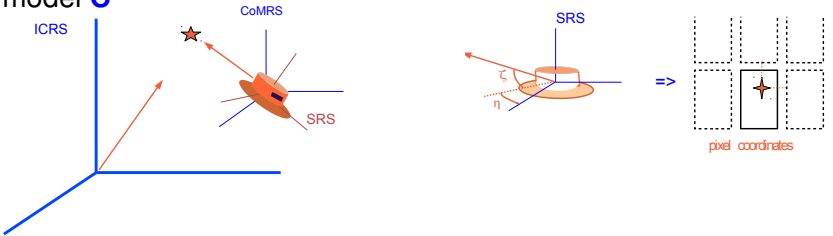
Gaia Focal Plane



Look at one block: Source modeling

The mapping or modeling of the observables **g** is done by three successive transformations:

1. from astrometric parameters to the celestial directions of a star at the instant of observation, using an astrometric model **S**
2. from celestial to instrument frame directions using an attitude model **A**
3. and finally from instrument directions to detector coordinates using an instrument model **C**



Source Update

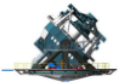
We fit the model to the observations:

Least squares for source update

$$\mathbf{A}\mathbf{x} \sim \mathbf{b} \pm \sigma \tag{2}$$

$$\text{where } \mathbf{b}_i = \mathbf{y}_i - f_i(\mathbf{a}, \mathbf{q}) \tag{3}$$

Here $\mathbf{y}_i$ are the observed field angles f_i is a function to calculates field angles from the current model.



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In java (SourceUpdateCalculatorWrapper):

```
// get calculated angles + derivatives ...
ExtendedFieldAngles ecfa = angleCalc.getCalculatedEtaZeta(ae, origSrc, UpdateBlock.Source.getId());

// ... from those, get just calculated angles
double[][] calcEtaZeta = ecfa.getEtaZeta();

// ... and the observed ones from the angle calculator
double[][] obsEtaZeta = angleCalc.getObservedEtaZeta(ae);
```

Its all team work on big projects

The END

Blast 20 Cerro Pachón April 2011.

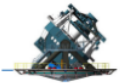
Questions?

Gaia blast off on Soyuz December 2013

http://www.lsst.org http://community.lsst.org http://www.cosmos.esa.int/web/gaia

Acronyms I

Acronym	Description
AU	deprecated acronym for astronomical unit, use au instead
AURA	Association of Universities for Research in Astronomy
C	Specific programming language (also called ANSI-C)
CU	Coordination Unit (in DPAC)
DM	Data Management
ESA	European Space Agency
ESAC	European Space Astronomy Centre (VilSpa)
ESOC	European Space Operations Centre (ESA)
ESTEC	European Space research and TEchnology Centre (ESA)
GB	GigaByte
HEALPix	Hierarchical Equal-Area iso-Latitude Pixelisation
HSC	Hyper Suprime-Cam
HTM	Hierarchical Triangular Mesh
K	Kelvin; SI unit of temperature
L2	Level 2 (ambiguous could mean milestone or processing)
LSST	Large Synoptic Survey Telescope
M	Mega; SI units prefix for 1E6
NASA	National Aeronautics and Space Administration (USA)
NEO	Near-Earth Object
NGC	North Galactic Cap
PB	PetaByte



Acronyms II

PSF	Point Spread Function
PhD	Doctorate in Philosophy
S	Strip (CCD chip along-scan coordinate identifier in focal plane)
SDSS	Sloan Digital Sky Survey
USA	United States of America
UTC	Coordinated Universal Time
W	Watt; SI unit of power
arcmin	arcminute, minute of arc (unit of angle)
arcsec	arcsecond, second of arc (unit of angle)
deg	degree; unit of angle
k	kilo; SI units prefix for 1E3
kg	kilogram; SI unit of mass
mu	micro; SI units prefix for 1E-6
n	nano; SI units prefix for 1E-9

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