GaiaFUN

GBOT – one year before launch

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GBOT=Ground Based Optical Tracking

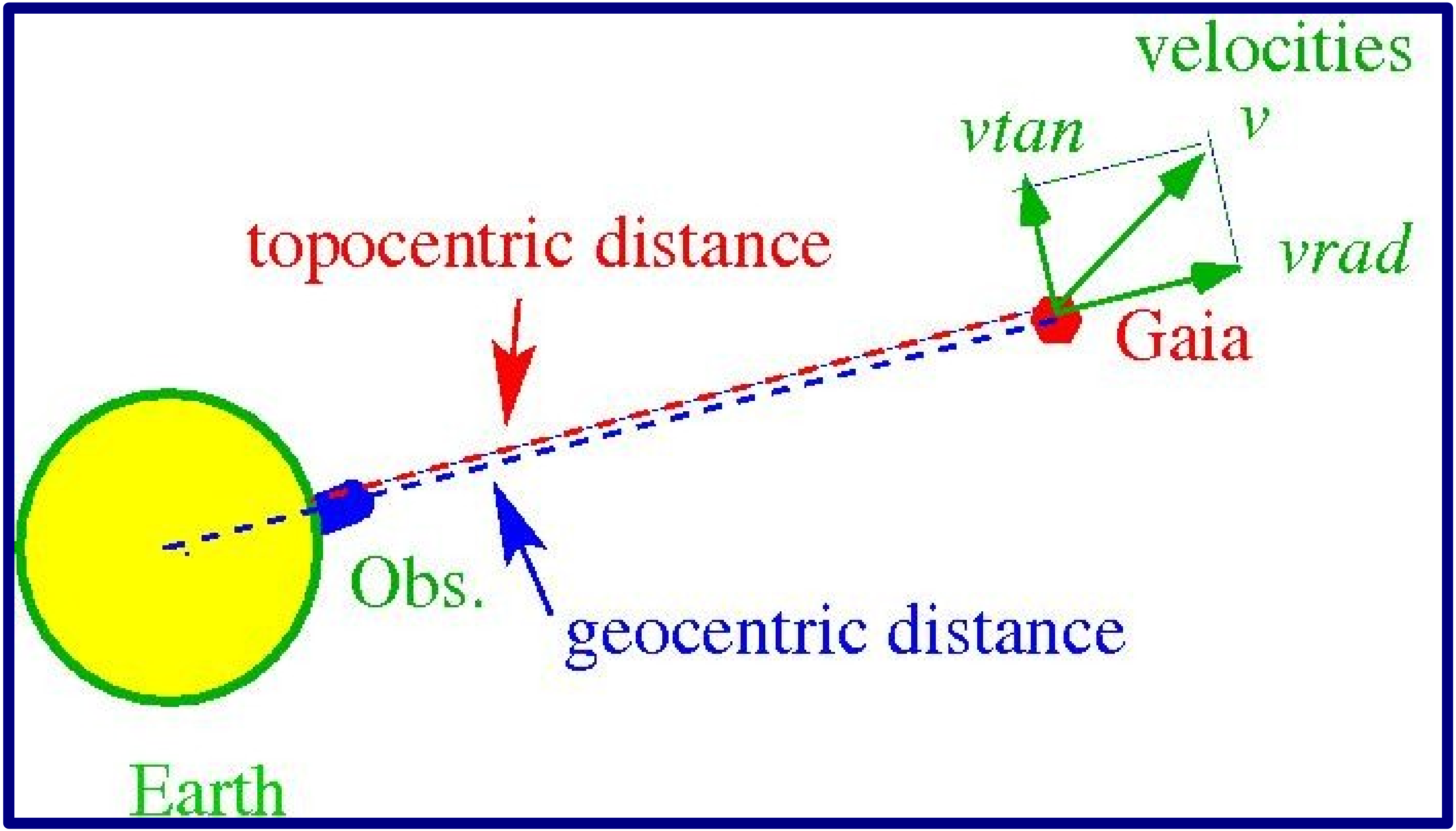
Why do we need **G**round **B**ased **O**ptical **T**racking?

- The highly ambitious aims of the Gaia mission requires very precise knowledge of the satellite's whereabouts so that the orbit can be reconstructed
  - Gravitational deflection of light by planets and **especially relativistic aberration**
  - Parallaxes of solar system bodies very sensitive to baseline
- Single tracking station does not suffice!
  - Second tracking station too expensive
  - Ground based optical tracking
  - Self calibration by reconstruction of lightpath (Klioner et al., Dresden)

Recap

Task at hand: Evaluating, testing methods and organising a world wide observing campaign of Gaia

GBOT: coordinates & definitions



Requirements:

Requirements & basic parameters:

- Distance Gaia-Earth: 1.5 million km
- Diurnal motion of Gaia: up to 2 degrees/day (usually about 1 degr/day)
- Positional & velocity precision requirements: 150 m & 2.5 mm/s (1 mm/s systematic).
  - Tracking station delivers 2000 m & 10 mm/s (75 m & 1 mm/s in radial direction)
- Translated to angular: 21 mas/29.7 mas/d
- Commitment: 10 mas/10 mas/d
- Time stamp: 0.1 s
- Positional precision of observatory: 10 m
- Early phase (before availability of Gaia data for calibration): Precision only 50-100 mas (due to precision limits of available reference catalogues)

Recap

Requirements:

Telescope specifications:

•Minimal mirror diameter: ~1 m

•Pixel scale: 0.3xmedian seeing

.

•Observatory needs to be able to supply data on a regular base.

•Ideally robotic or remote controlled telescope or with long term observational program

•Telescopes on both hemispheres required

•Aim is to get about 3-6 regular contributors and some backups.

•Recruitment of observatory partners started 2009 & ramps up now

Recap

GBOT: The Team

The GBOT task force consists of astronomers from 5 countries:

- Martin Altmann (Heidelberg, Germany, coordinator)
- Alexandre Andrei (Rio de Janeiro, Brazil)
- Christophe Barache (Paris, France)
- Uli Bastian (Heidelberg, Germany)
- Sebastien Bouquillon (Paris, France)
- Teddy Carlucci (Paris, France)
- Sebastian Els (Madrid, France), Project office liaison
- Francois Mignard (Nice, France)
- Luciano Nicastro (Bologna, Italy)
- Ricky Smart (Torino, Italy)
- Iain Steele (Liverpool, UK)
- Paolo Tanga (Nice, France)
- Francois Taris (Paris, France)

(in alphabetic order)

GBOT is part of the GBOG (Ground Based Observing Group)

GBOT: The Team

The team is geographically dispersed communications absolutely vital:

- Monthly telecons, dealing with current subjects
- 6 monthly meetings
- Regular trips of M.A. To Paris
- Extracurricular telecons and visits
- Wikipage (a.k.a. Wikibible)
- Documentation
- Close communication between GBOT(MA) and high level (T.Prusti, PO, etc.)

GBOT: The Team

The GBOT team faces several challenges:

- Establishing and developing observing methods for a faint and moving object
- Choosing suited observing sites worldwide and negotiating deals with observatories and TACs.
- Developing software and a database system, which allows for easy and straightforward data reduction and analysis (astrometry) of inhomogeneous data from diverse sources.
- In the operating phase: coordinating observations, data reduction and delivery

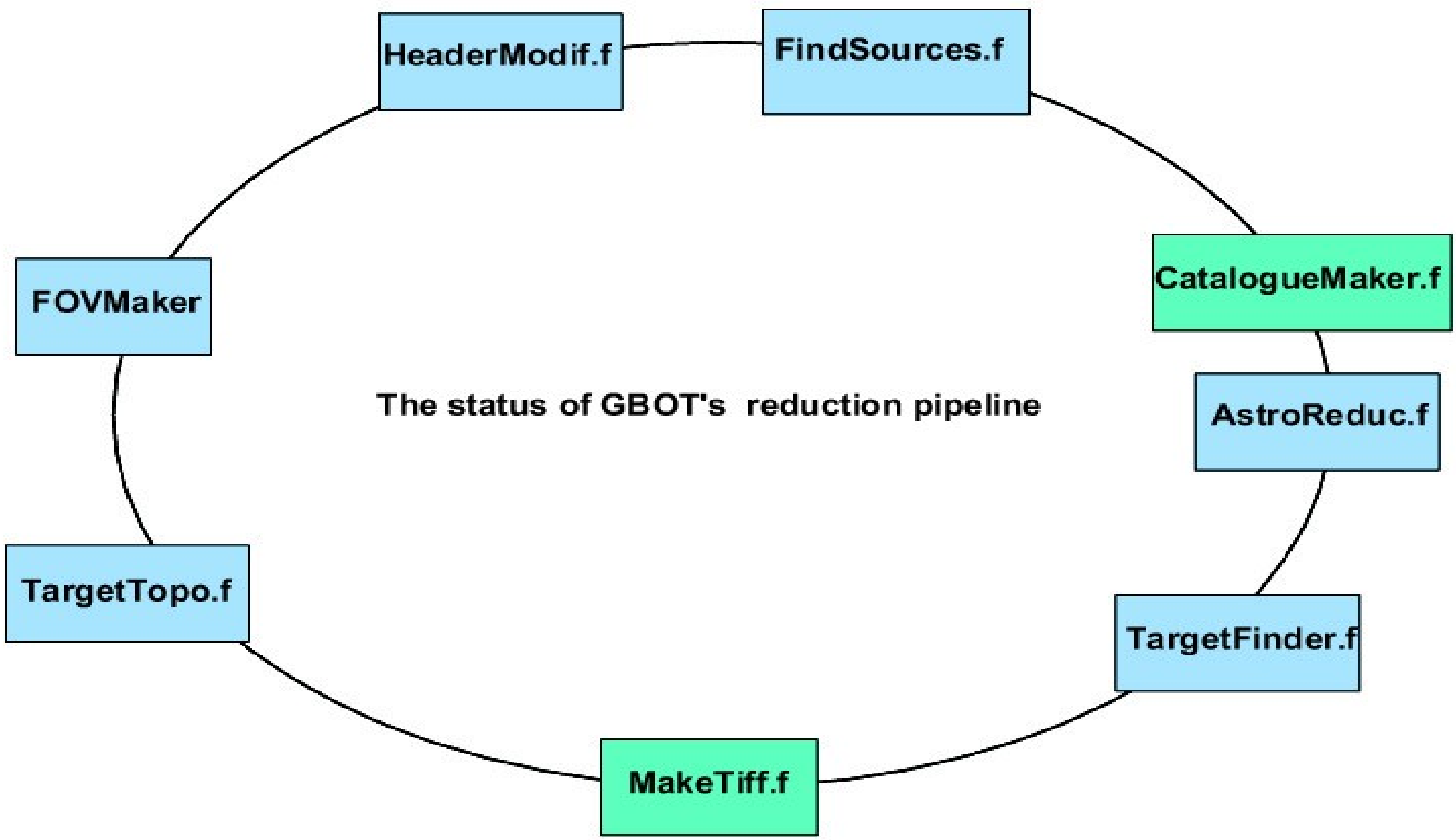
GBOT: the pipeline

(S. Bouquillon & F. Taris with A. Andrei, R. Smart, M. Altmann):

- Allows high precision and accuracy astrometry of a faint moving target
- Copes with data from different sources
- High degrees of flexibility, several centroiding algorithms
- Diagnostic output
- High level of automatisation
- Current status: operative, reaches specs, will still be continuously improved

The GBOT Pipeline:

Diagram of routines (courtesy S. Bouquillon/F. Taris)

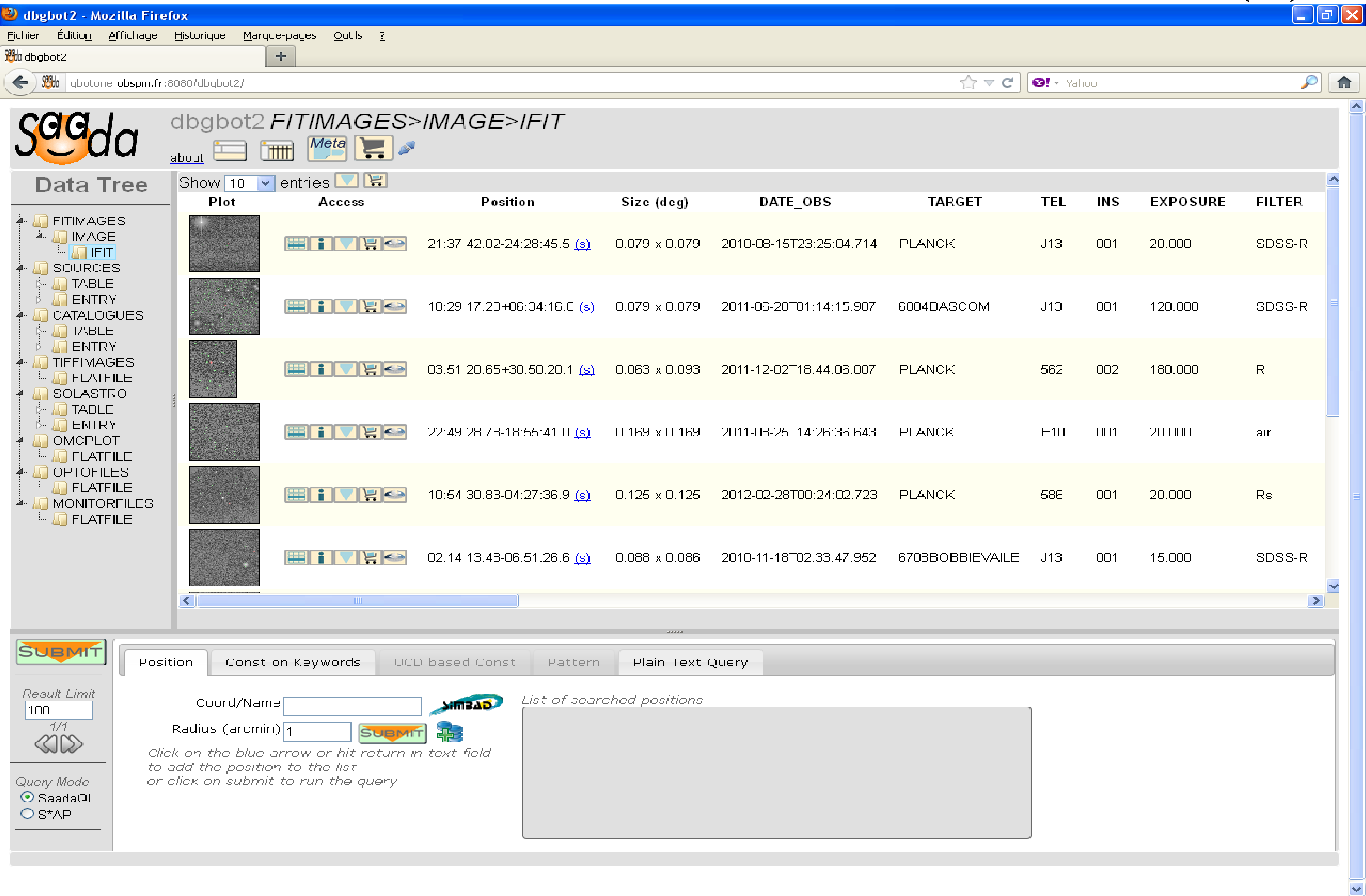


GBOT: The Database

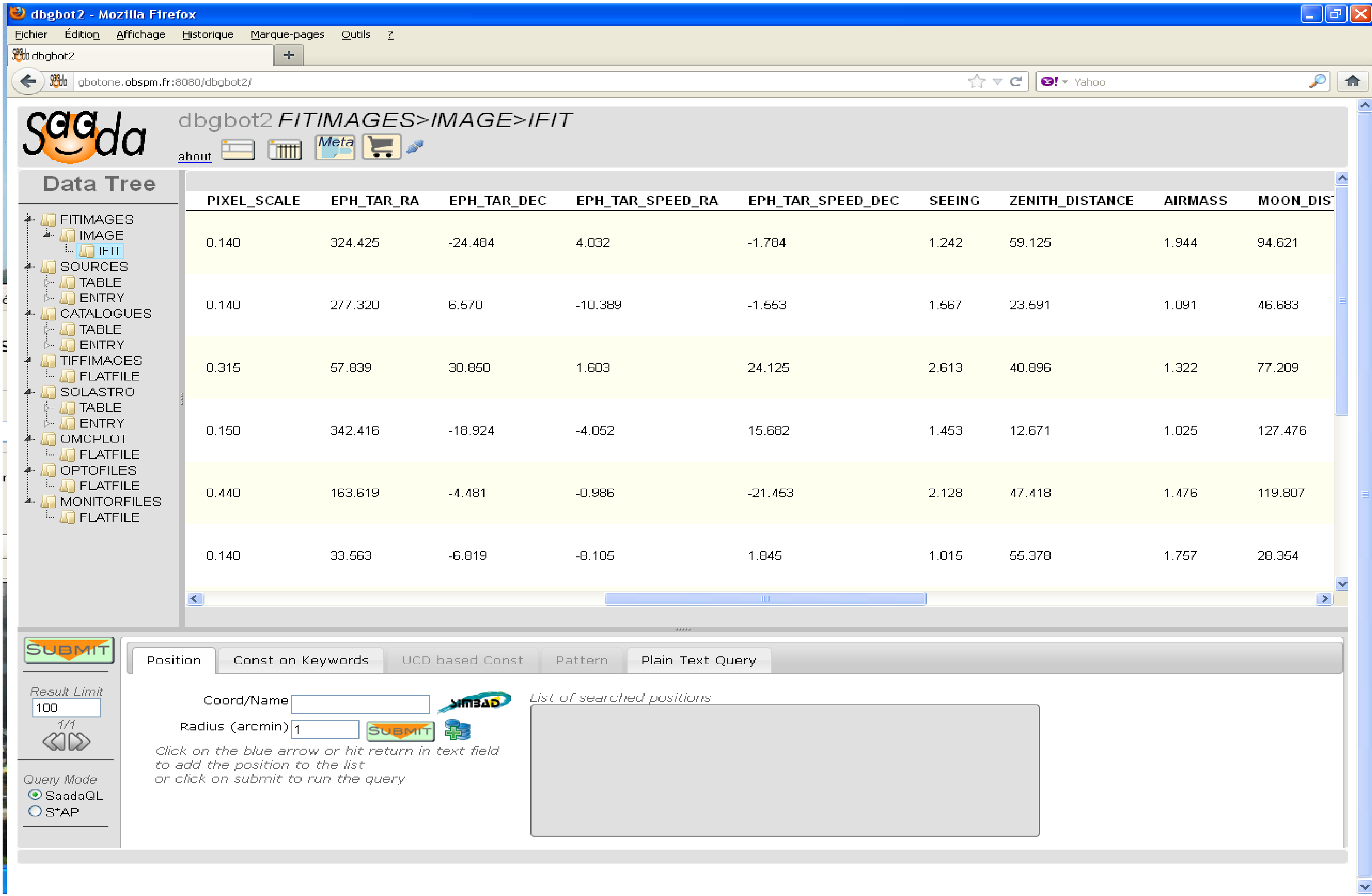
(C. Barache, T. Carlucci, S. Bouquillon & F. Taris with L Nicastro, R Smart, M.Altmann):

- Store and manage data from different inhomogeneous sources
- Store products, diagnostics, metadata
- Access from different locations (Paris, Heidelberg, Torino, the beach, Mount Everest, etc.)
- Mirror system (Paris and Heidelberg
- Construction of GBOT SAADA DB started 2011
- Highly developed version will be ready for DPAC-OR2 (Dec 2012)
- Issue: Hardware both in HD and Paris

Saada – Collections FITIMAGES (1)

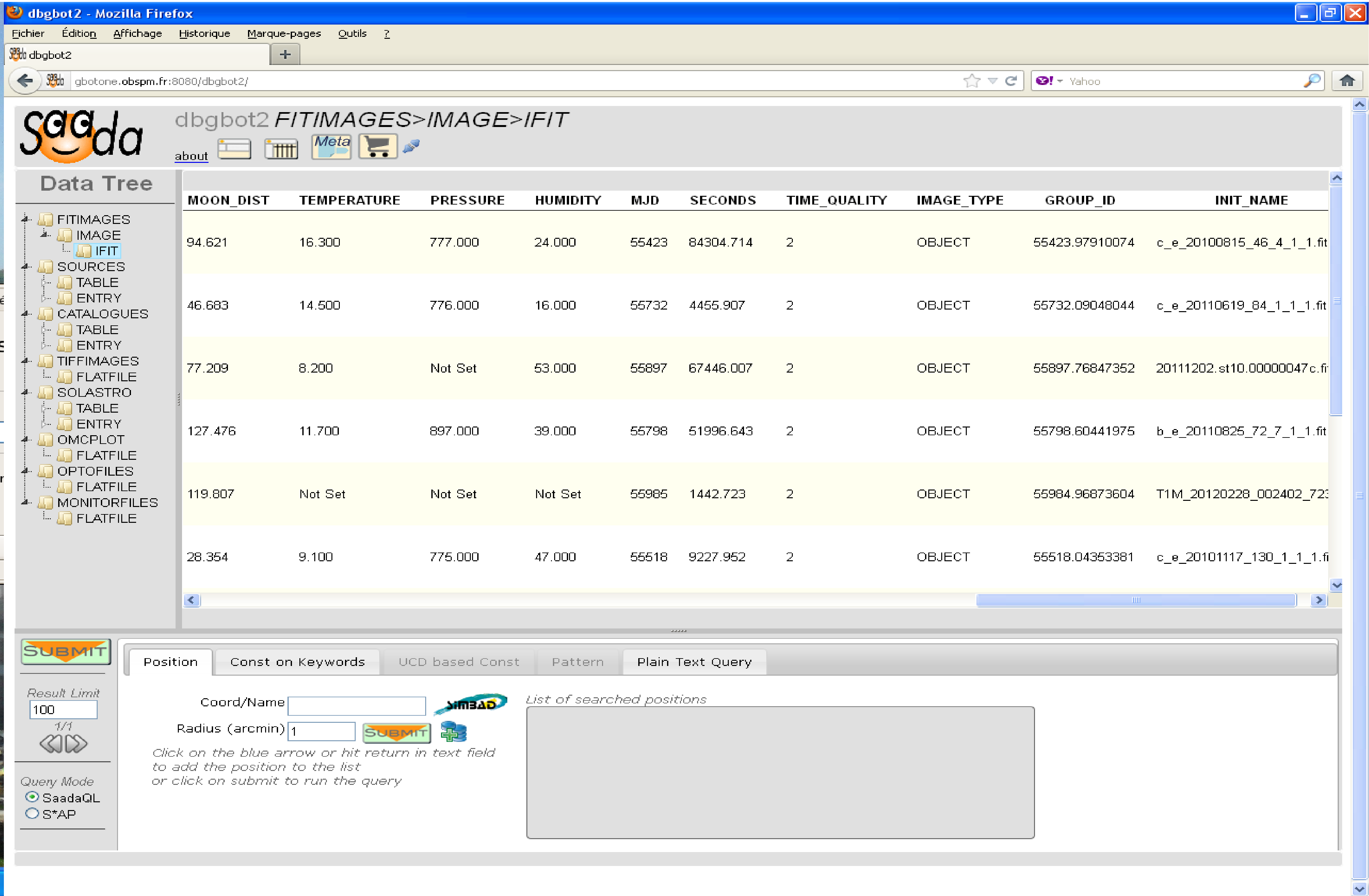


Saada – Collections FITIMAGES (3)



PIXEL_SCALE	EPH_TAR_RA	EPH_TAR_DEC	EPH_TAR_SPEED_RA	EPH_TAR_SPEED_DEC	SEEING	ZENITH_DISTANCE	AIRMASS	MOON_DIST
0.140	324.425	-24.484	4.032	-1.784	1.242	59.125	1.944	94.621
0.140	277.320	6.570	-10.389	-1.553	1.567	23.591	1.091	46.683
0.315	57.839	30.850	1.603	24.125	2.613	40.896	1.322	77.209
0.150	342.416	-18.924	-4.052	15.682	1.453	12.671	1.025	127.476
0.440	163.619	-4.481	-0.986	-21.453	2.128	47.418	1.476	119.807
0.140	33.563	-6.819	-8.105	1.845	1.015	55.378	1.757	28.354

Saada – Collections FITIMAGES (4)



Observatory Recruitment:

Observatory Recruitment:

- Recruitment of (at least) 4-6 partners with regular contributions
-
- Information leaflet written, informing and motivating prospective partners
-
- Set of tests to evaluate potential partner facilities established
-
- Cooperation with other DPAC units requiring ground based support during the mission (Science Alerts, Asteroids) – synergy effects!

Observatory Recruitment:

Problems and difficulties:

- Data & operation modes very diverse
- Data FITS headers sometimes lack important information, such as object position (Camera and Telescope system not connected)
- In some cases proposals necessary
- Position of telescope on Earth from MPC often dubious (not precise enough, reference point and global system not known)

- ***Problem: many facilities in danger of being closed down or at least with unsure future (e.g. LT).***

Good news: more robotic networks coming up, Las Cumbres, Koreans

Observatory Recruitment:

- **Liverpool Telescope (Partner) 2m (RdlM)***
- ***Faulkes N+S 2m (clones of LT), Hawaii & AUS (negotiating partnership),*** *acc. Proposal,* ***testing***
  - LCOGTN is setting up a network of 5x3x1m telescopes*
- Zadko (W-Aus), ***testing postponed, techn problems, image scale***
- ESA 1.3m (Canary Islands) *image scale*
- Figl 1.5m, AT, ***testing****
- Euler&Merope ***testing, promising***
- MEO (F)?
- PdM* (F) 1.06m, ***testing, promising***
- **VATT (V),** *starting tests in autumn*
- MONET ***fallback solution***
- PAN-STARRS ***will deliver serendiptious measurements***
- ***ESO* VST-Omegacam: testing, is being negociated by Timo Prusti***
- Nainital ***(India)***

Observatory Recruitment:

"All we hear is" Radio GBOT, Radio GBOT, Radiooo.
– using VLBI to track Gaia:

- Gaia is bright in the Radio-regime
  → VLBI can observe using the smaller dedicated units only
- Ultra precise positions
- Presumably not daily, rather monthly, fundamental QSO must be nearby
- Maybe VLBI can help calibrating timestamps?
- May help narrow the Full Moon gap

Observatory Recruitment:

"All we hear is" Radio GBOT, Radio GBOT, Radiooo. – using VLBI to track Gaia:

- Currently we are determining the scope of the VLBI contribution and laying out a roadmap (that's why I am here :-)

ere

- First observing campaigns underway (using Planck), new proposal will be prepared for submission in October.
- As with the other parts of GBOT, VLBI observations will start, when Gaia is in its final L2 location

It may well be that GBOT="Ground based ***OPTICAL*** tracking" turns into: GBOT="Ground based ***ORBIT*** tracking"

GBOT: the Timeline

GBOT- *Historic Timeline*:

- **2008:**
  - Kickoff, evaluation of methods and feasibility
- **2009-12:**
  - continuation of testing, test runs
  - establishment of contacts to observatories, TACs, etc.
  - Defining requirements based on tests.
  - Other preparations, software development, database etc.
- **2012-13:**
  - final selection of participating observing stations & backups
  - Test runs & DPAC OR's (GBOT: partly SCI)
  - Documentation
  - Conclusion of all preparatory activities
- **2013-20:**
  - **Launch & Operational phase**

GBOT: the Timeline

GBOT- *Zoomed in Timeline 2012-13*:

- **2012-13:**
  - final selection of participating observing stations & backups
    - Partner recruitment will be active to the end of the OP
  - Test runs & DPAC OR's (GBOT: partly SCI)
    - OR1 (July) GBOT low level participation: successful
    - OR2 (Dec) Full participation with LT
    - OR3 (Mar '13) LT & LCOGT
    - OR4 (???) all available telescopes
    - Internal test runs to check PL,DB communication
  - Documentation
  - Conclusion of all preparatory activities
- **2013-20:**
  - **Launch & Operational phase**
  - ~2015 Rereduction of all data from launch - 1st AGIS
  - End of Datataking: Final GBOT reduction of all data

Delivery:

We are committed to deliver to ESOC (MOC, Flight Dynamics)

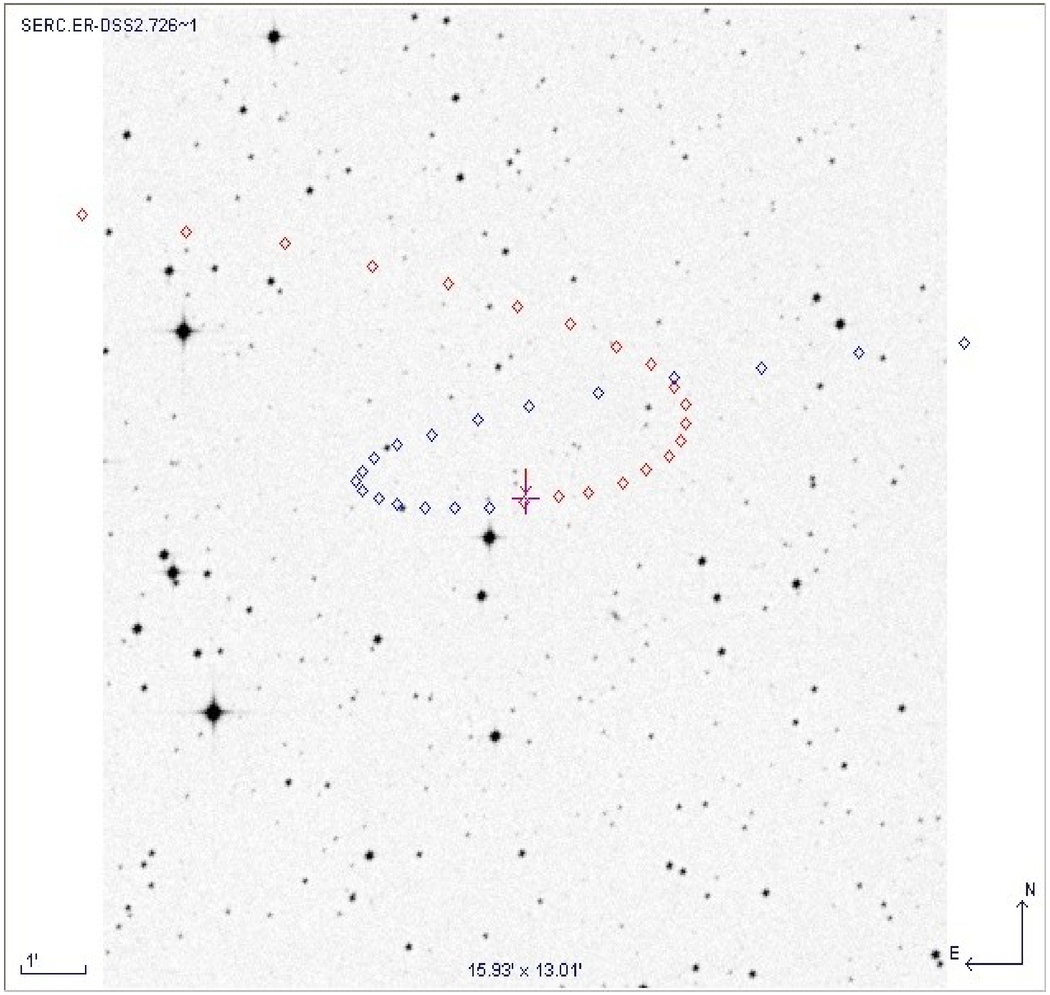
- For every day: fully reduced and analysed topocentric celestial coordinates

- Precision (of complete observation) 10 mas & 10 mas/d

- Delivery schedule: monthly

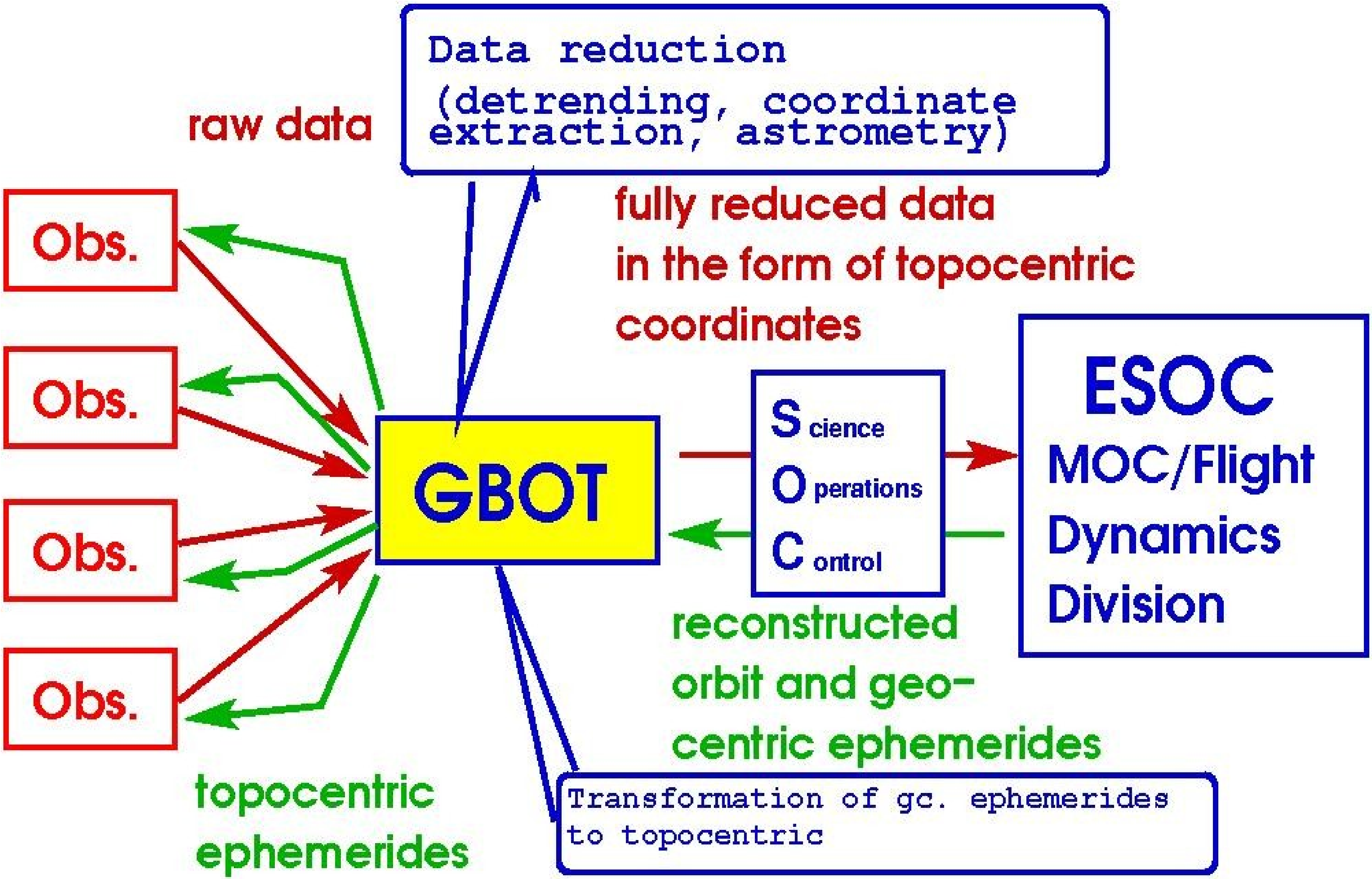
- In turn we'll receive ephemerides from FD which will be distributed to the observatories topocentralised to their coordinates.
- We will receive the first reliable Gaia data and rereduce all GBOT data to meet specifications

Delivery: diurnal motion of L2-satellites



We will have to deliver every data point obtained in the night rather than some average

Delivery:


Data reduction
(detrending, coordinate extraction, astrometry)
raw data
fully reduced data
in the form of topocentric
coordinates
Obs.
Obs.
Obs.
Obs.
GBOT
S cience
O perations
C ontrol
ESOC
MOC/Flight
Dynamics
Division
reconstructed
orbit and geo-
centric ephemerides
topocentric
ephemerides
Transformation of gc. ephemerides
to topocentric

Problems & Chances:

- Observatories face closure (Hoher List) or have an insecure future
- Some partners need financial support in order to be able to participate
- Those groups, that require ground based observations during the mission (GBOT, SSO, Gaia Science Alerts)
  - Often similar facilities are needed
  - Observations can often be done in a complementary way
  - Efforts can be concertated, synergy effects exploited

Finale: *Open issues & resume:*

- Gaia's brightness
- Reduction procedures and software
- Recruitment of cooperating observatories
- Observing test runs on greater scale

The first two years have brought GBOT on the right track, now we are coordinating and intensifying our efforts to find the optimal solutions – and assemble a set of observatories with suited equipment, people (directors, observers, TACs) who are willing to dedicate some of their time to Gaia!

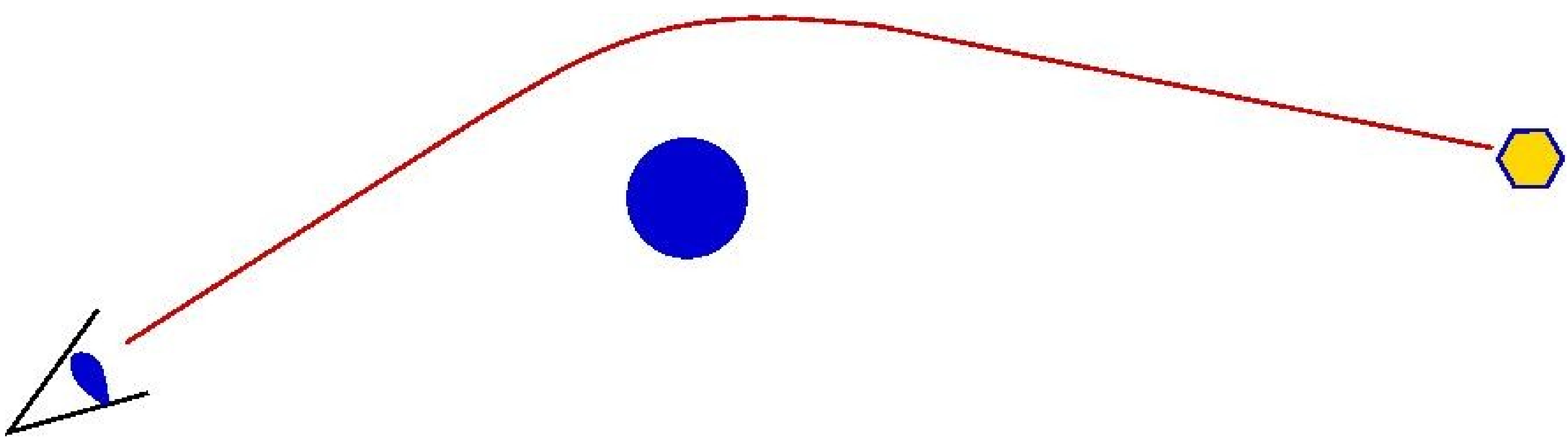
Bottom Line: "Yes we can!"

But it ain't easy

GBOT: The main effects (reasons)

Deviation of light (lensing) by solar system bodies

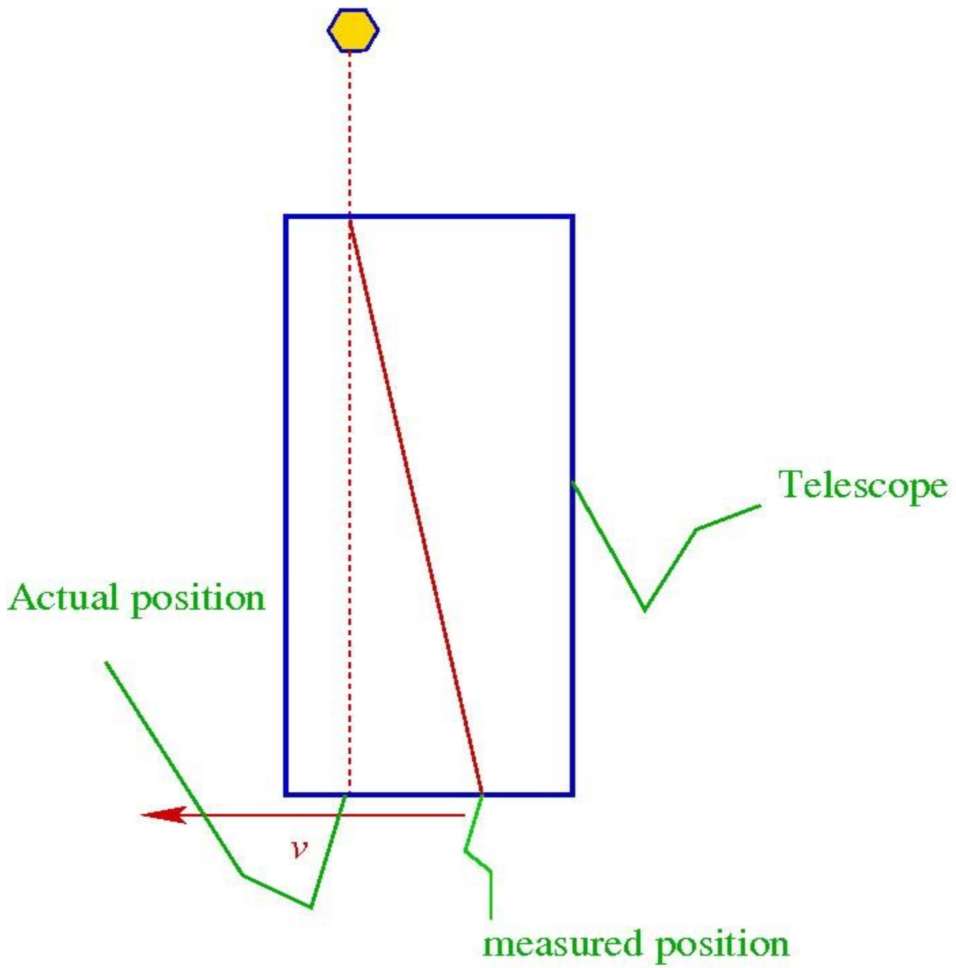
- All masses influence the path of light
  - Light as Gaia sees it is bent by the masses of the Sun and all major Solar System bodies
  - In order to reconstruct the light path, hence to correct the measured position of an object, the satellite's 3D position within the Solar System needs to be known very precisely



GBOT: The main effects (reasons)

(Relativistic) aberration of light

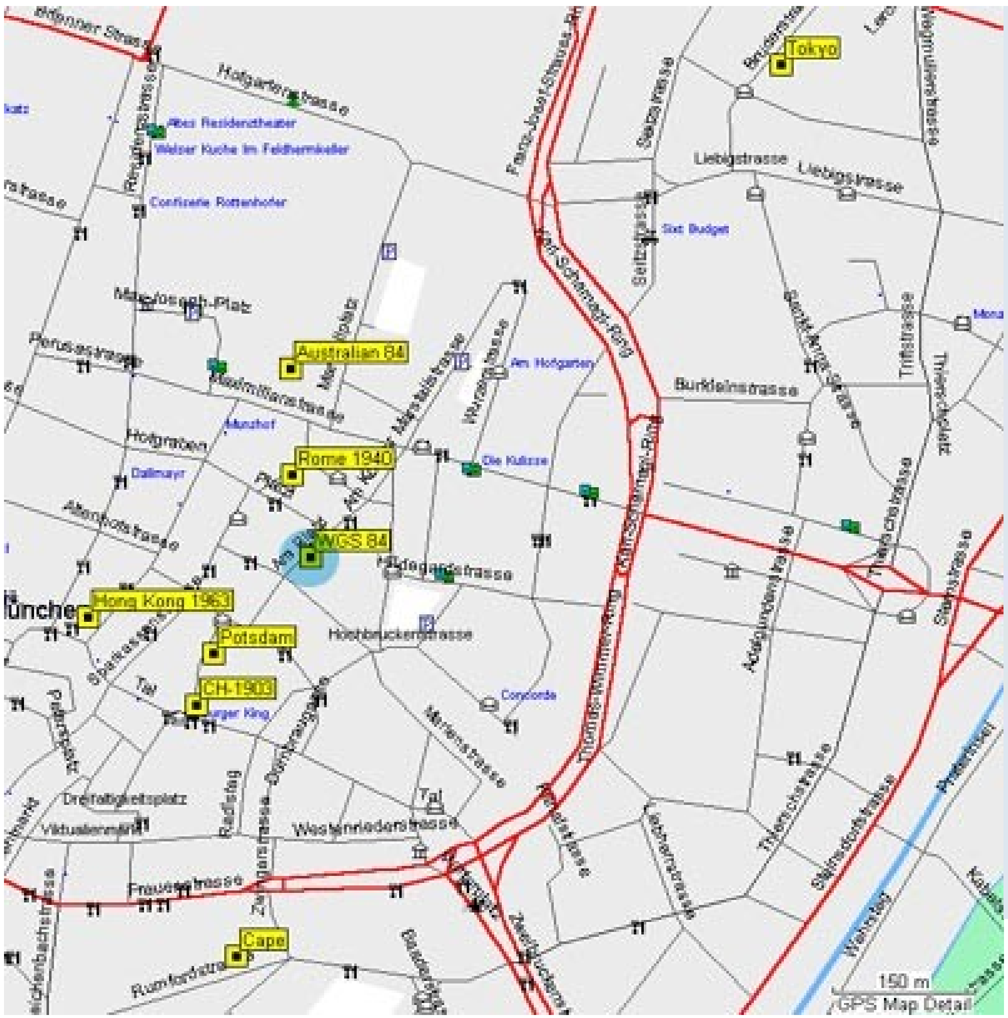
- The light velocity is finite!
  - Light falling onto a detector moving transversal to the beam deviates from its nominal intercept point by the detector's movement

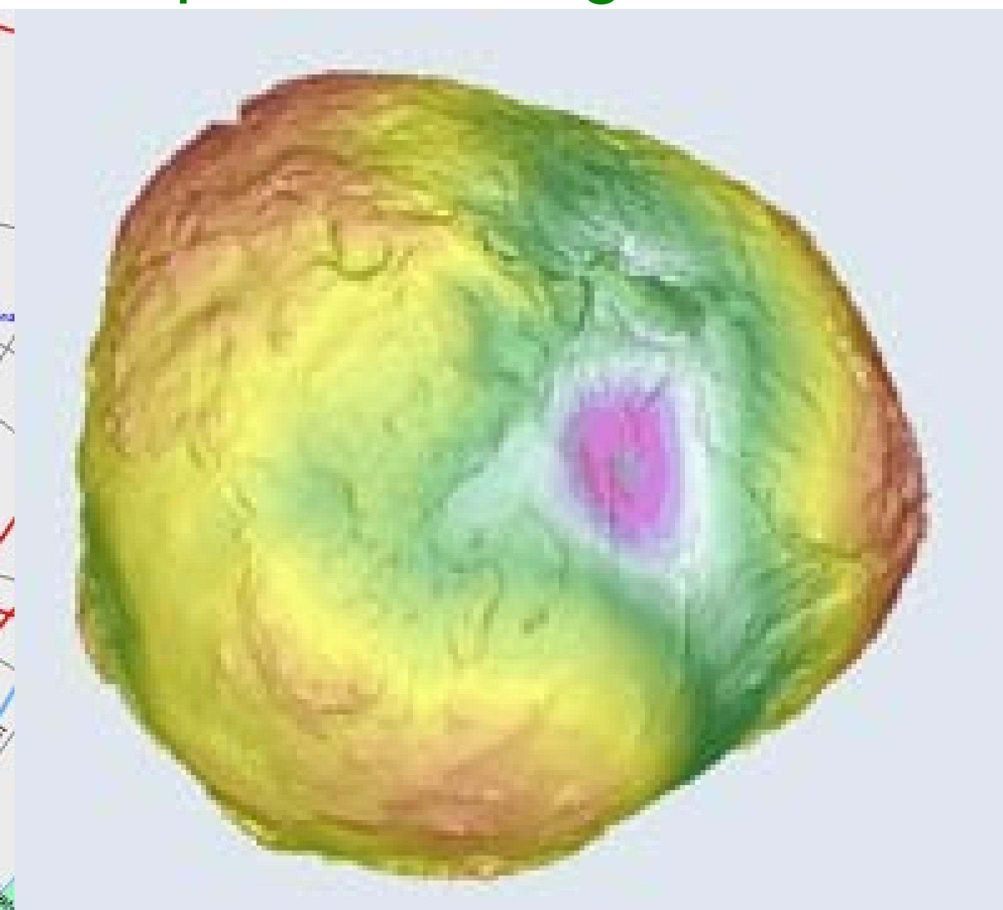


Coordinates of Observatories:

Determination of terrestrial coordinates:

- Is far from straightforward, and subject to earth models
- Earth is not round, neither an ellipsoid, but a geoid

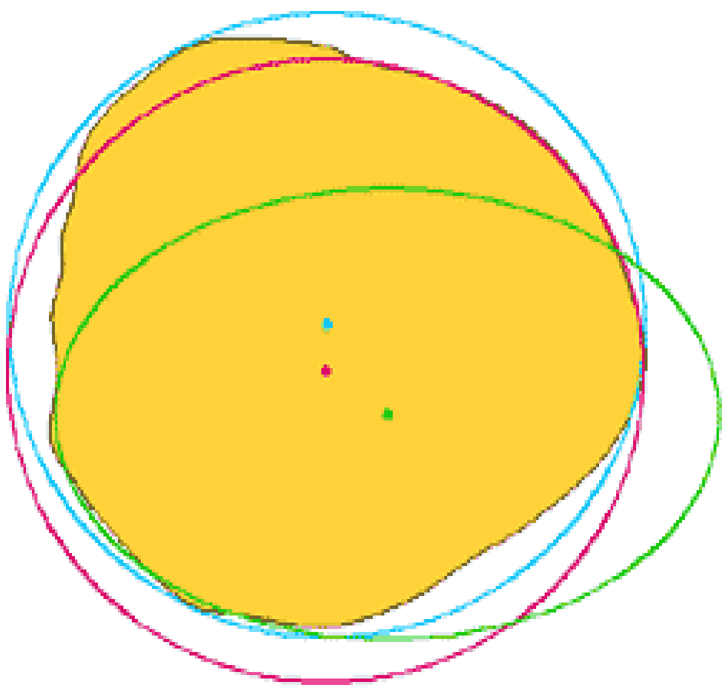


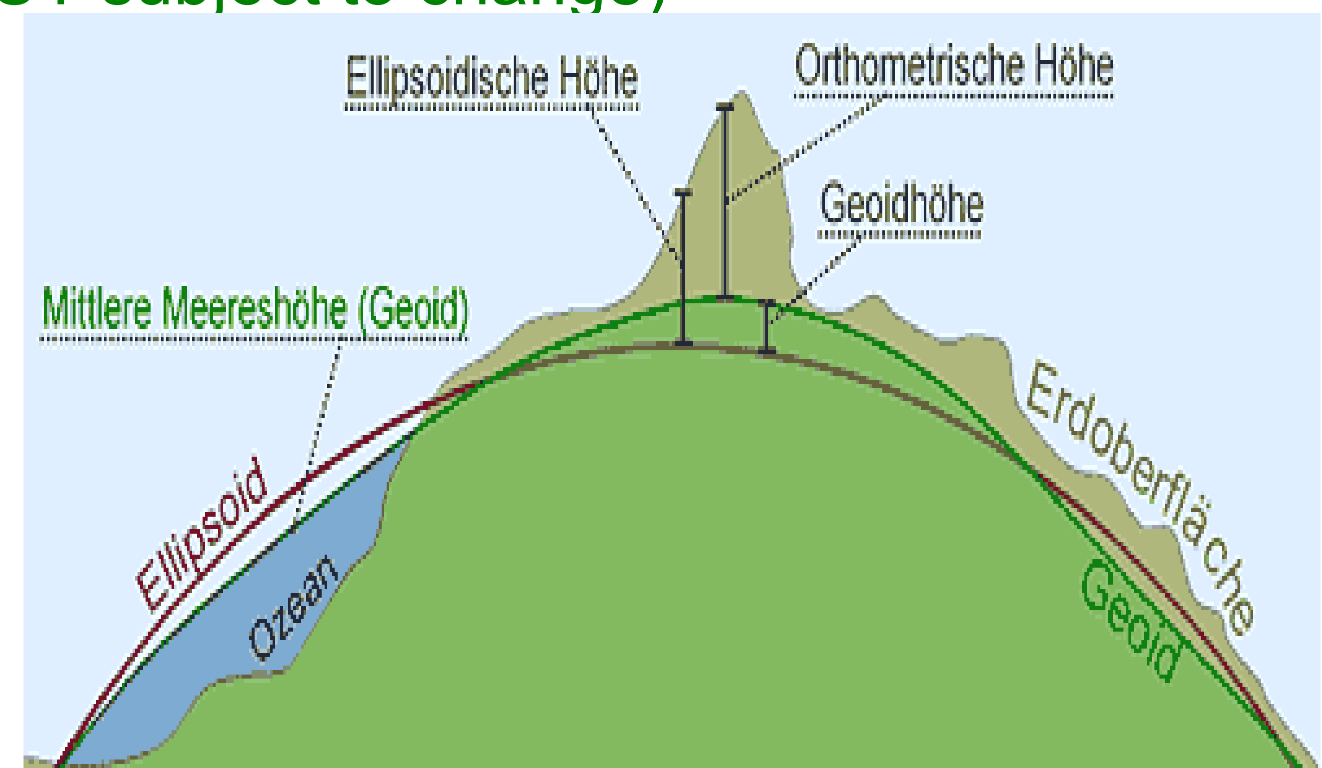


Coordinates of Observatories:

Determination of terrestrial coordinates:

- Several ellipsoids possible, none is optimal
- Current Standard model WGS84 consists of WGS84 ellipsoid+EM96 lookup table
- GPS uses this model and interpolates between the gridpoints of the lookup table
- Model (especially LUT subject to change)





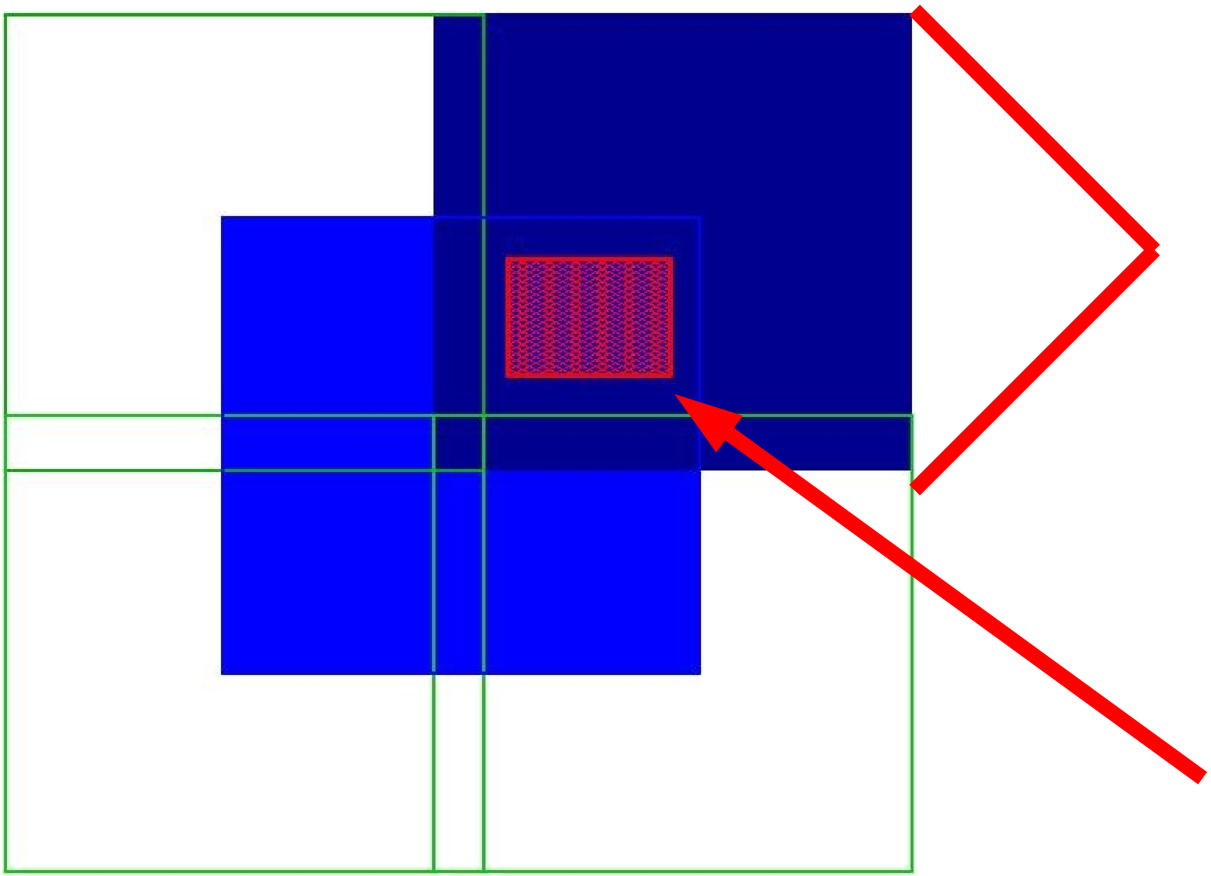
Observations

First observations:

- First attempts hampered by erroneous ephemerides.
- After acquisition of ephemerides from the WMAP team itself, WMAP was observed for the first time on April 5, 2008 with WFI at the 2.2m/La Silla
- Second successful observations with the 1.06 m telescope at Pic du Midi
- Test Observations will continue in 2010 to test methods, precision (under different circumstances), etc., also using minor planets as additional guinea pigs.

Observations:

Example: WFI – Mosaic vs. single chip using the SEPC data:



1 WFI field (4x2 CCD), each subfield consists of 5 dithers so that gaps are closed

Selected field (not to scale)

mosaic (assembled from 5 dithered pointings vs. single eposure

Observations:

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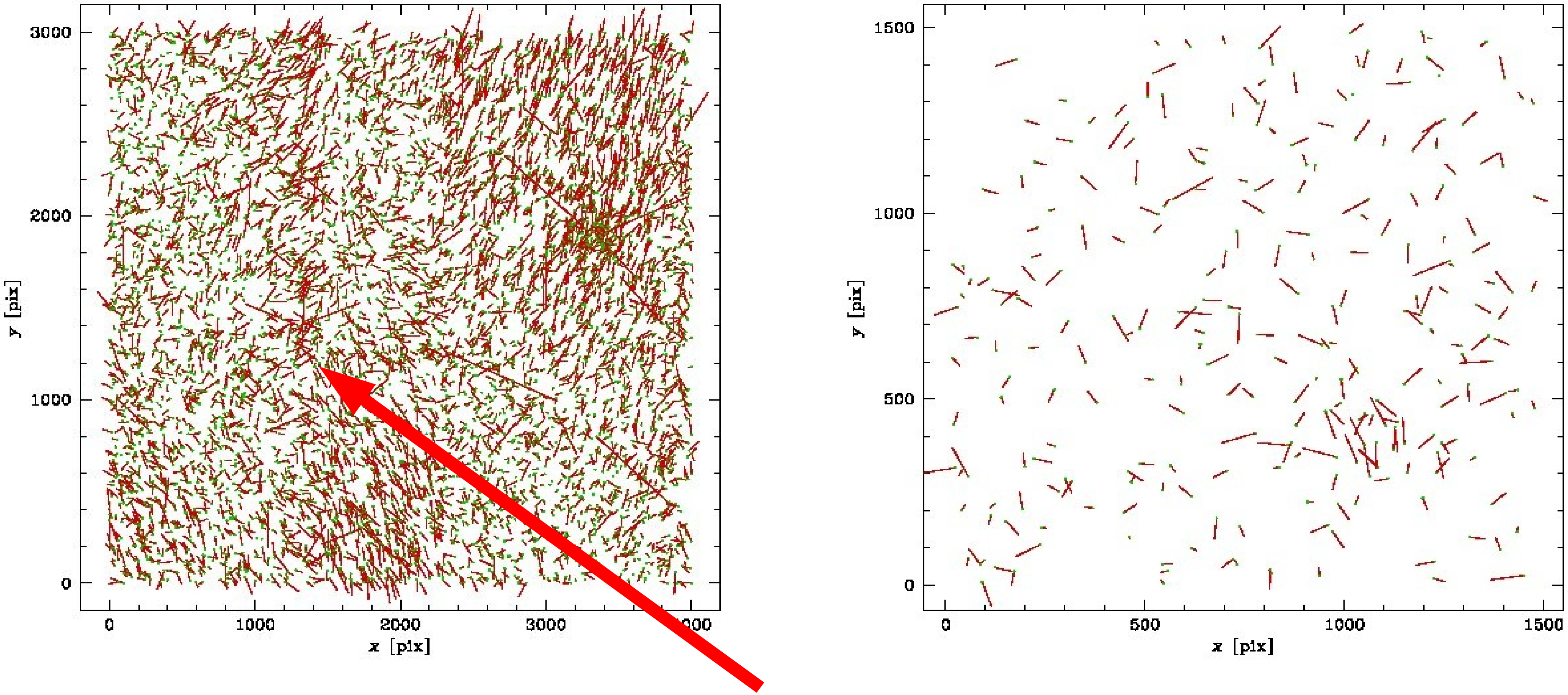

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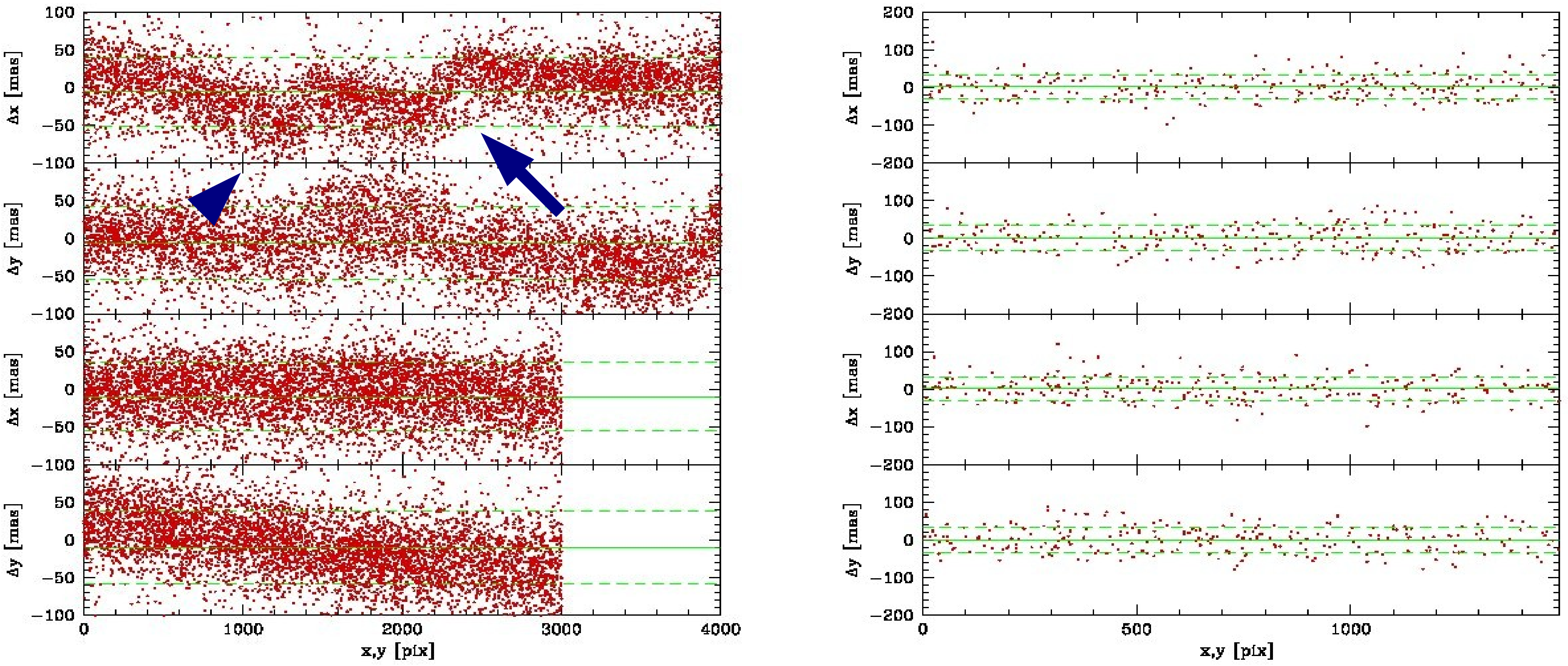


mosaic (assembled from 5 dithered pointings vs. single eposure

Requirements:

GBOT vs. Science Alert Follow up:

GBOT

- Astrometric precision paramount
- Object, position and planned observations known beforehand
- As much automatisation as possible
- Daily availability of network to be ensured
- Huge and regular influx of data: Good database and reduction pipeline needed
- Worldwide network of telescope to ensure coverage

SAFU

- Photometry and spectroscopy
- Positions, number of triggers completely unknown
- Human genius needs to be involved
- Daily availability of network highly desirable
- Huge and regular influx of data: Good database and reduction pipeline needed
- Worldwide network of telescope to ensure coverage

Requirements:

GBOT vs. Science Alert Follow up:

- There are distinct differences between GBOT and an approach to Science Alert follow up; However there is also much in common
- GBOT and SAFU are the only(?) auxiliary programmes to be active during the whole Gaia operational phase.
- Some of the telescopic resources can be shared
- SAFU will also need reduction pipeline and database system
- SAFU and GBOT can help each other in the Observatory partner recruitment
- Look for possibilities of synergy effects
- Much of the GBOT preparations (remainder of this talk) may also be of relevance to SAFU

The brightness issue:

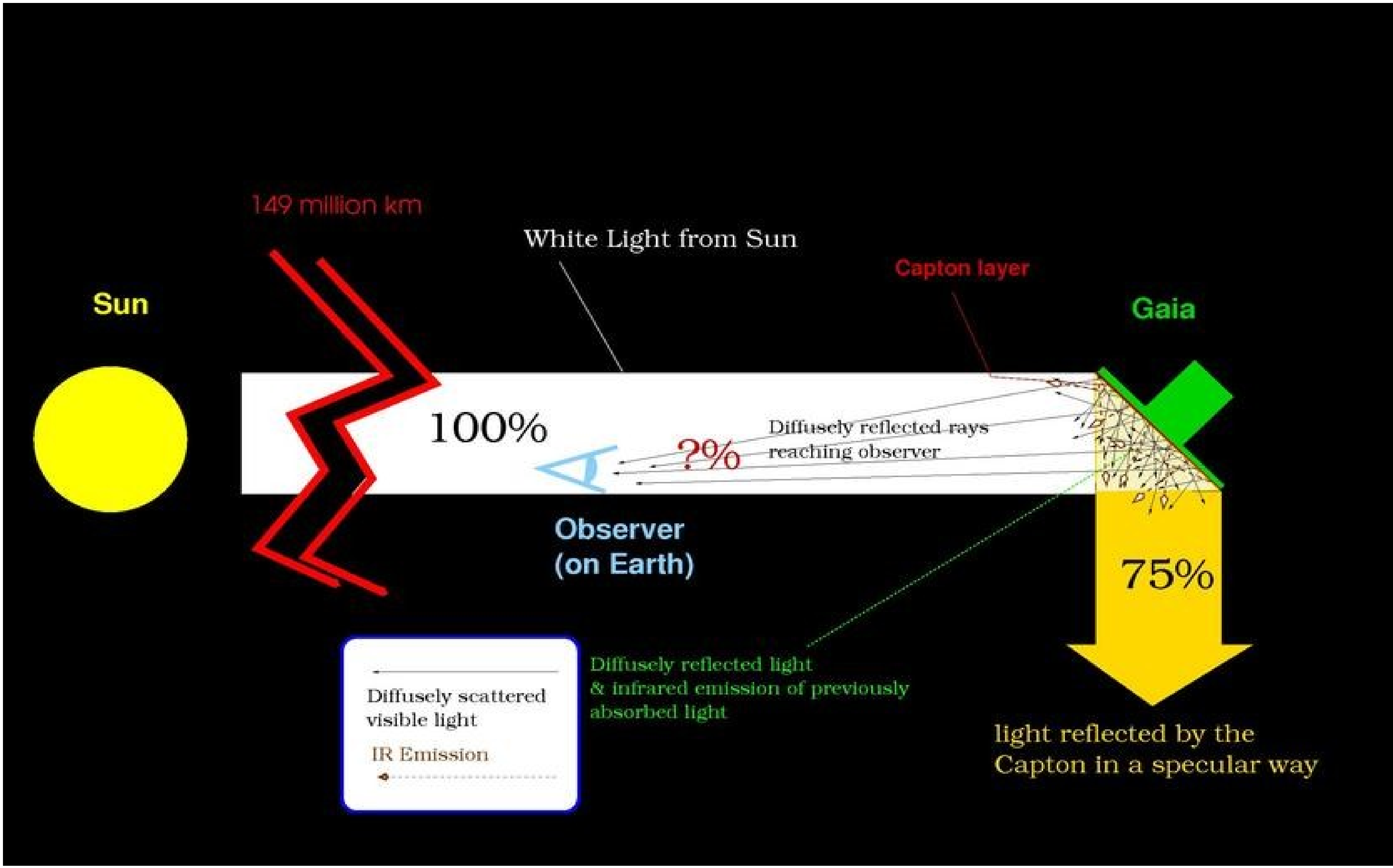
How bright will Gaia be?

- Gaia's thermal shield is mostly covered by Kapton mylar and Solar panels

- The plane of the shield is inclined by 45 degrees, i.e. the specular reflection beam points 90 degrees away from Earth

- Only light reflected by imperfections, such as wrinkles and other structures like antennae, etc. is observable

The brightness issue:



The brightness issue:

How bright will Gaia be?

- Dedicated Lab studies to estimate the probable fraction of reflected light measurable on Earth are not feasible, due to costs and uncertainties

- studies of the reflective behaviour of the Kapton type to be used for Gaia exist (confidential, sorry), which seem to indicate a higher percentage of diffuse reflection.

→ **Gaia could be rather brighter than the smaller spacecraft WMAP & Planck**
(This would greatly simplify our task)

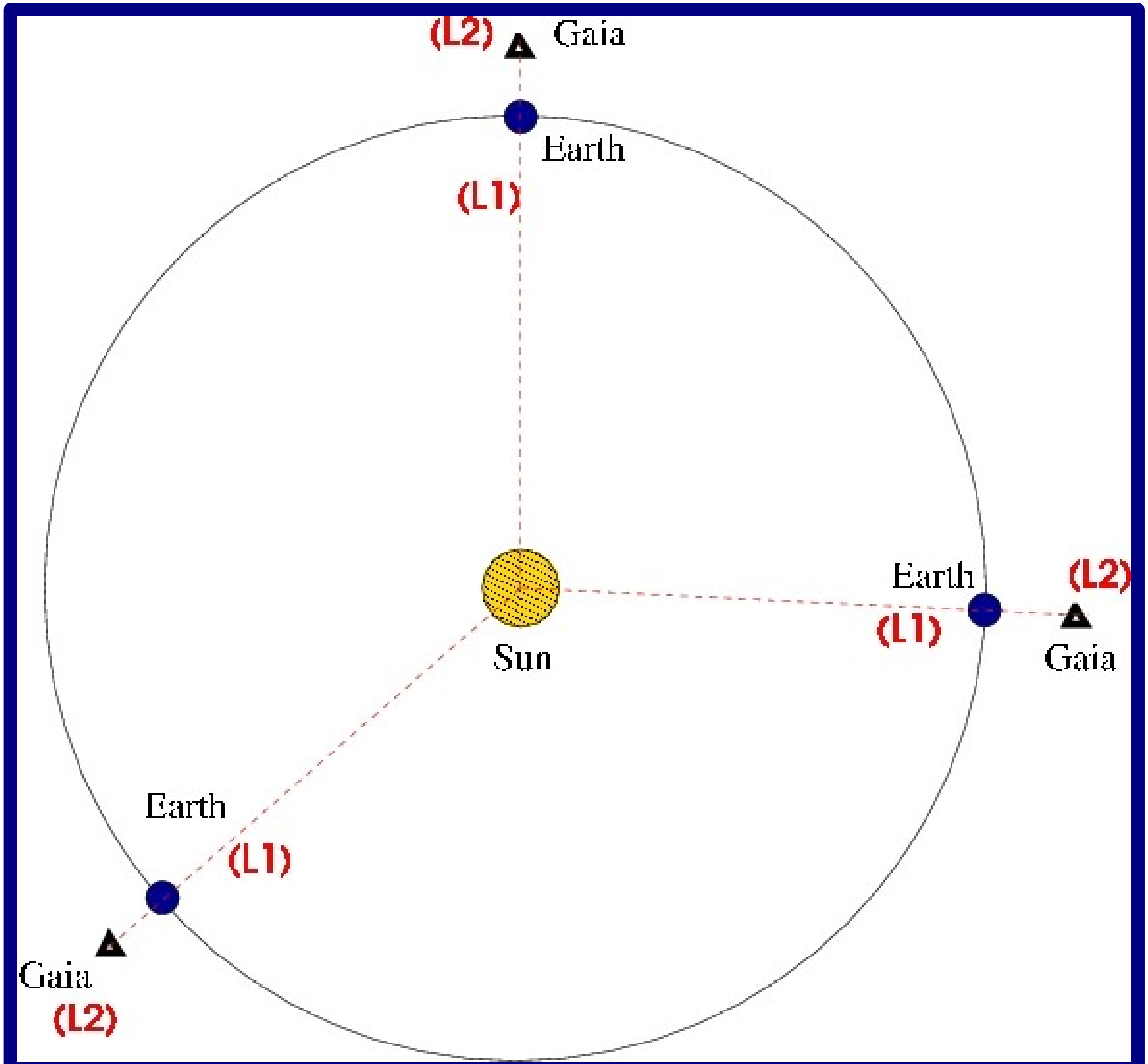
The brightness issue:

WMAP, Planck & Herschel to the rescue!

- We do not have a quantitively reliable estimate of Gaia's brightness
- WMAP (diameter 5 m, inclination angle 22.5 degrees) has an overall similar structure as Gaia (diameter 11 m, inclination angle 45 degrees), PLANCK has different structure
- Brightness of WMAP 18.5-19.2 mag in *R*-band and Planck 17-19.
- Gaia is assumed to have similar brightness (due to its larger diameter it could be significantly brighter, the working base Is ***R*(Gaia)=*R*(PLANCK)!**)

Expected brightness of Gaia remains uncertain and still is under significant debate – and will only be known with cerrtainty when Gaia is at L2

Gaia's Orbit

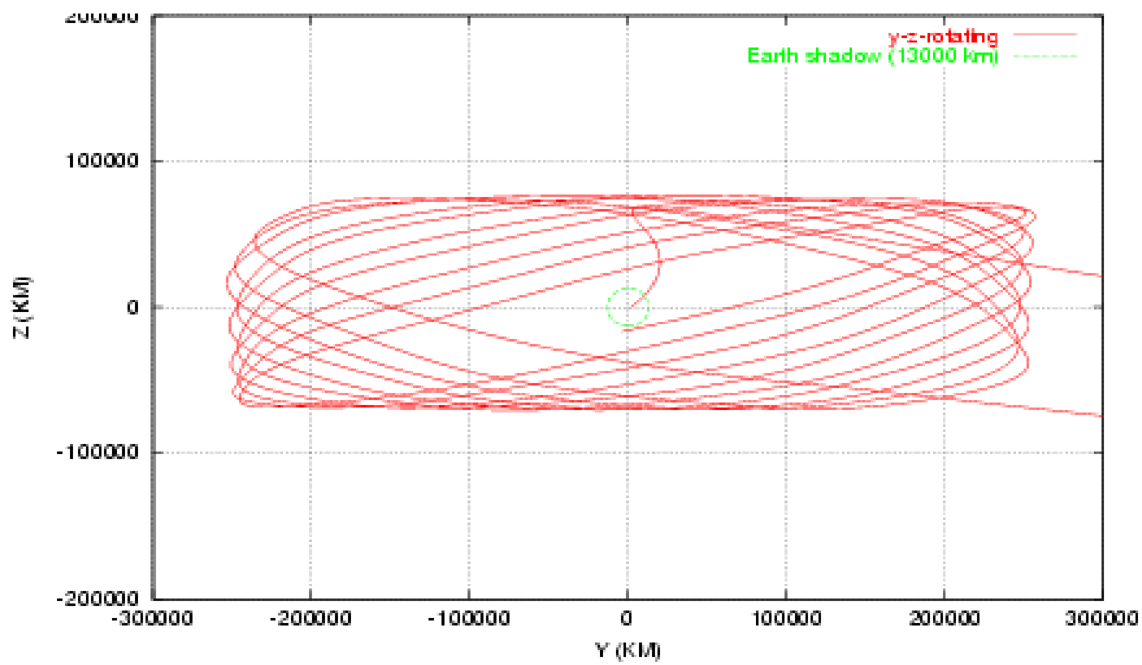


Orbit of L2 (Gaia) in respect to Earth's orbit around the Sun

($d_{Earth\text{-}Gaia}$=1.5x10[6] km)

Gaia's orbit around the L2 Lagrangian point

Figure 3: Orbit with radiation pressure



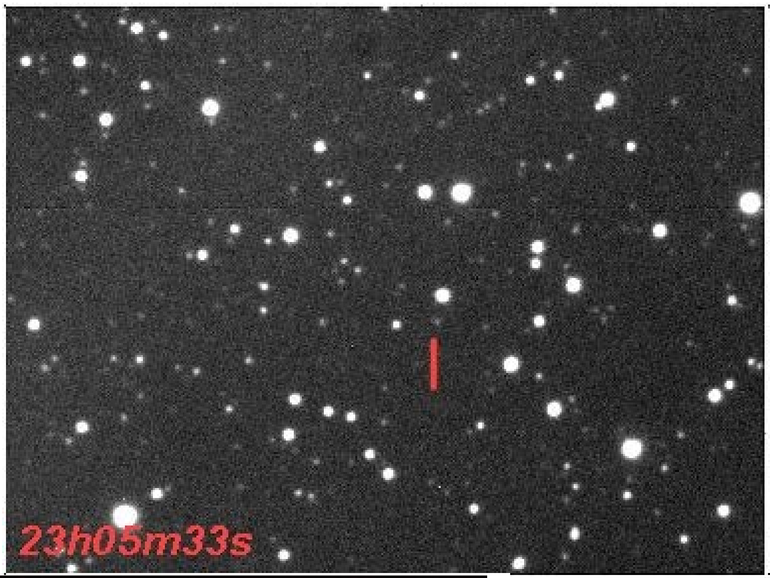
- Orbit actually unstable, 6 monthly corrective boosts in the order of mm/s necessary
- The orbit needs to be know to 150 m in position and 2.5 mm in velocity!
- Satellite needs to be monitored using tracking station *and* optical telescopes (***G***round ***B***ased ***O***ptical ***T***racking)

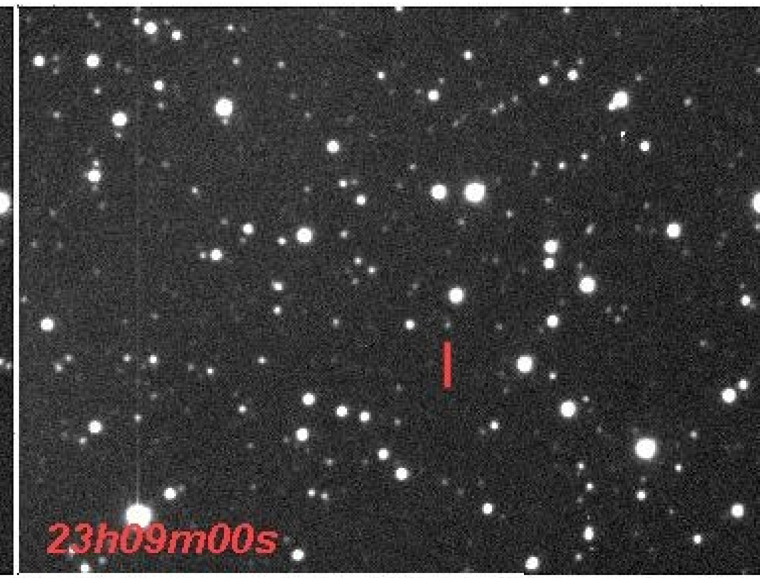
Observations

First observations:

13.7.2008,
PdM 1.06m

5.4.2008,
ESO-La Silla
2.2m+WFI





F.Colas

Observations:

Test results derived from WFI , Liverpool Telescope, Pic du Midi 1.06 m, OHP 1.2m and Hoher List 1.06 m data, Figl Obs., MEO:

- Precision compared to UCAC**2** ~40 mas, newest results from LT are even better (Do not use UCAC3 for δ>-20°)

- Constraints on maximum exposure time and image degradation due to object motion

- No observations possible at full moon (±1-2 days, Moon near L2)

- Detailed analysis of field structure of WFI data with different pointings show feasibility (using single chip data)

- Mosaic not suited for our purpose (though a single chip of a Mosaic could be used)

- Set of standardised tests for prospective partners established

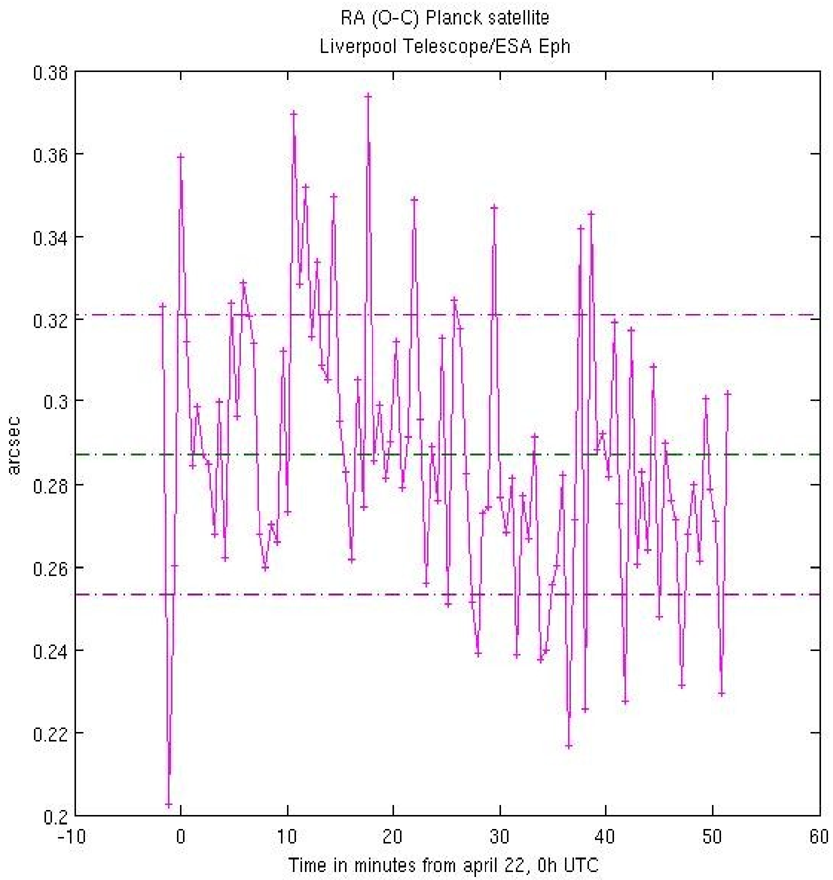
Observations:

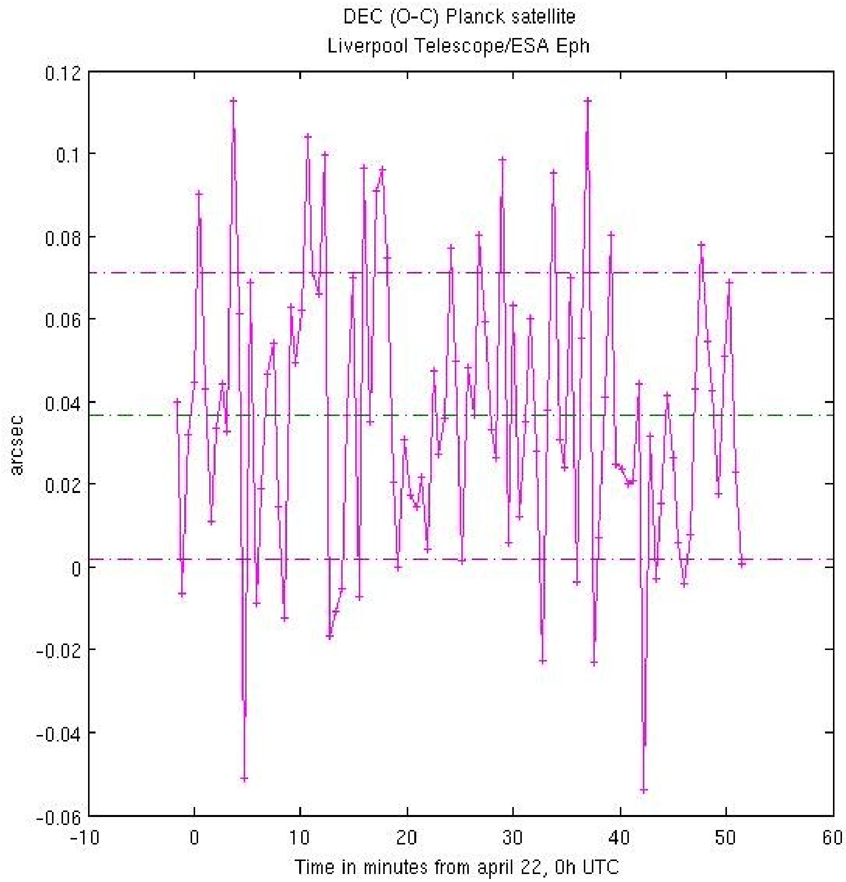
Advanced mid term test campaigns to test operational feasibility (LT):

- **<u>Planck</u>** observing test campaign in August/September (following an officia request by ESOC):
  - For 4 weeks, weekly observations
  - 1 week: daily observations
  - Additional data from other telescopes & times

- Proposal based test campaign with binary asteroids as science case (PI.: P. Tanga)
  - 20+20 hrs in two semesters

Observations:

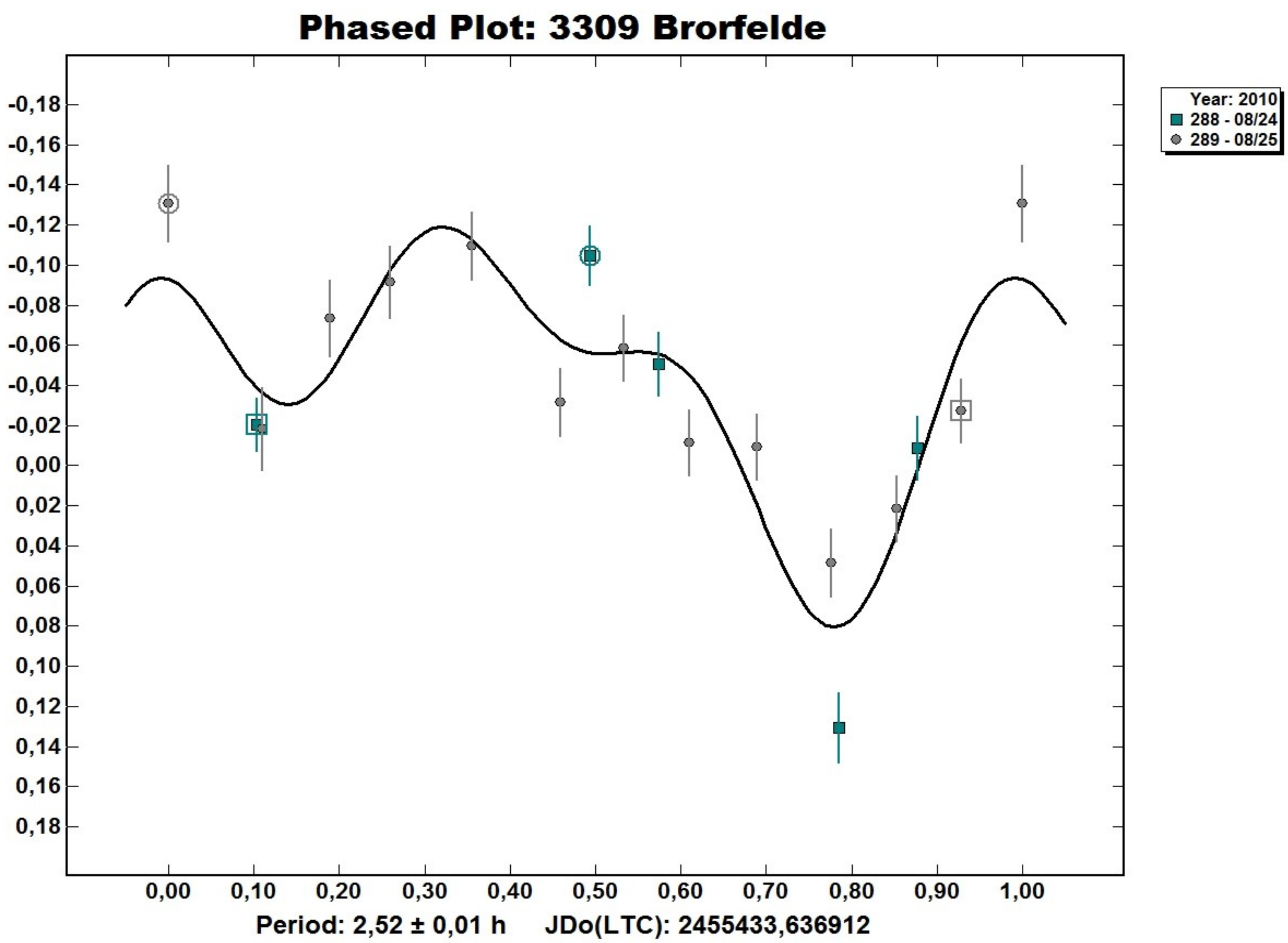




Latest Results from test observations of PLANCK with the Liverpool Telescope and the first ones reduced with the GBOT-pipeline:

Ref. Cat.: UCAC2, shown O-C(Eph.), *sigma=35 mas*

Observations:



Lightcurve from the binary Asteroid observing campaign with the Liverpool Telescope, featuring 3309 Brorfelde