Ground Based Observations of Gaia: First tests using WMAP

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Abstract

We discuss the first tests carried out with a goal of defining the procedures for the Ground Based Optical Tracking (GBOT) of Gaia. We have made observations of the Wilkinson Microwave Anisotropy Probe in both guiding-on-the-stars and guiding-on-the-satellite modes. We present the results of these tests and, considerations of the required detector size and proposed filter choice.
The GBOT program is evolving continuously and status, up-to-date discussions, known problems can be found at Gaia wiki page `http://www.rssd.esa.int/wikiSI/index.php?title=CU3:_Auxiliary_Data:_Ground-based_Optical_Tracking`

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Acronyms used in this document

The following table has been generated from the on-line Gaia acronym list:

Acronym	Description
CCD	Charge-Coupled Device
CReMA	Consolidated Report on Mission Analysis
DCR	differential color refraction
ESO	European Southern Observatory
GBOT	Ground-Based Optical Tracking
INAF	Instituto Nazionale di Astrofisica (Italy)
MCT	Ministerio da Ciencia e Tecnologia (Brazil)
PSF	Point Spread Function
SYRTE	Systemes de Reference Temps-Espace
UCAC	USNO CCD Astrograph Catalogue
UT	Universal Time
WFI	Wide-Field Imager (ESO 2.2-m telescope)
WMAP	Wilkinson Microwave Anisotropy Probe
WP	Work Package

1 Introduction

We report on observations made of the Wilkinson Microwave Anisotropy Probe (WMAP) satellite during the spring of 2008. These observations were carried out to test the feasibility of ground based satellite tracking with a realistic application for Gaia. The tracking requirements of the Gaia satellite have been a subject of substantial work with a goal to put into place a observational structure and description of requirements before launch. An explanation of the tracking requirements, activities for ground based optical tracking and future plans can be found at the wiki `http://www.rssd.esa.int/wikiSI/index.php?title=CU3:_Auxiliary_Data:_Ground-based_Optical_Tracking`

The Gaia tracking requirements are discussed in detail in the Consolidated Report on Mission Analysis (CReMA, Hechler & Landgraf (2008)) document. There the quoted velocity requirement is 2.5mm/s and 150m which in addition to radar tracking requires an observational campaign with a positional precision requirement of 20 mas. The current GBOT baseline includes another error buffer and has a per observation accuracy requirement of 10 mas. Current work is continuing under this assumption. However, we note the original requirement, based on a simplistic consideration of abberation, was 0.6mm/s which translates into a position precision 5 mas. In Mignard (2005)), based on the assumption that the departures from constant velocity between successive observations of the same target are small, it was been revised up to 2.5mm/s. Since this is such an important revision, and 5 mas is a much more challenging requirement than 20mas, we feel it is important that some simulations are carried out to quantify the the acceptable level of velocity departures between successive target observations and subsequent translation into a ground based accuracy be reviewed throughly.

One of the principal problems with ground based tracking of Gaia will be it's significant motion. The average motion of Gaia is basically a mirror of the solar motion, 41 mas/s, with the small orbital motion around L2 imposed on top. One of the principal questions that we hope to address before Gaia flies is to identify the best mode of observation. Three methods have been proposed and tested, tracking on the satellite and smearing the stars, tracking on the stars and smearing the satellite and making many short exposures tracking on the stars but then reconstructing the satellite image including the ephemeris motion. All three have pro's and con's some of which may actually not become apparent until we have a Gaia quality reference frame but testing today with relative comparisons is useful. For this we have attempted to observe the WMAP satellite.

2 Wilkinson Microwave Anisotropy Probe, WMAP

The selection of WMAP as a guinea pig for Gaia was due to its' similar orbit, size and sun shield material. Gaia will have a larger sun shield which we expect it to be brighter hence any results for WMAP will have an inbuilt safety margin. The WMAP satellite was observed on the ESO2.2m Wide Field Imager (WFI) in April 2008 (see appendix A) and on the Pic du Midi

1.06 m telescope in July 2008. It has a V magnitude that is variable and around 18 but to date we do not have much information on it's color, since the light we see is diffuse sunlight we will assume it's color is close to solar.

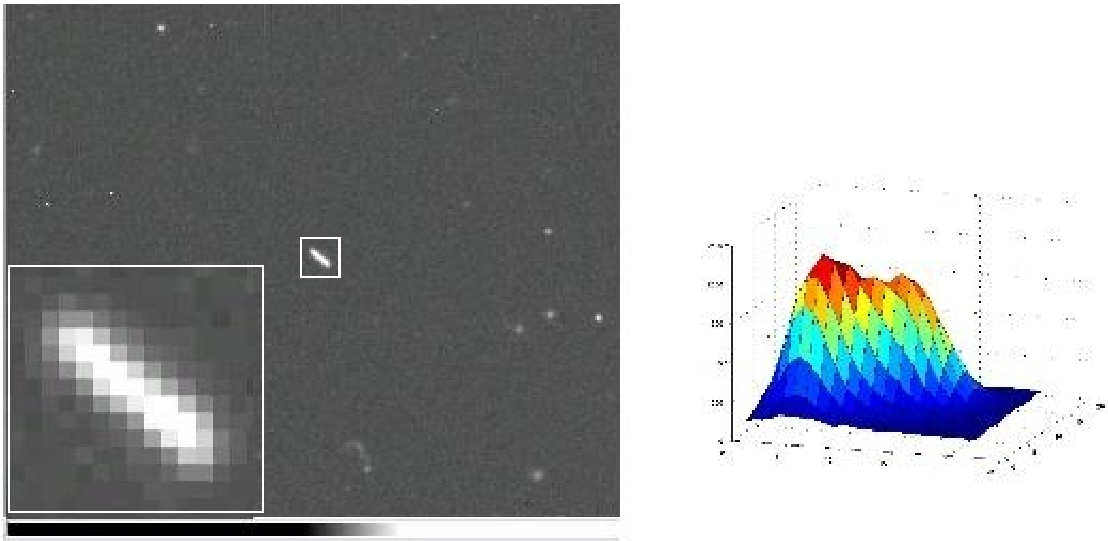

FIGURE 1: Left panel: A normal and zoomed view of a 300s, 2x2 binned image of the WMAP satellite taken on the ESO 2.2m telescope with the WFI.
Right Panel: The PSF of the satellite image.

2.1 Observations with Equatorial Tracking

In figure 1 we show a 2x2 binned 300s image of WMAP with the ESO 2.2 m telescope and Wide Field Imager in normal equatorial tracking mode. We find the positions of stars in the tracked frames using the SExtractor software with barycenter fitting and obtain a nominal formal error of between 60-80 mas. The point spread function of the satellite is shown in the right panel of figure 1 for which it is not possible to give a precise estimate of the positional precision.

One estimate for the overall precision in equatorial tracking mode can be found by comparing many short exposures of the satellite to its nominal ephemeris. To this end we observed the satellite 20 times with an exposure time of 15s tracking always on the stars as shown in figure 2. The path of the satellite during this time is seen as three tracks and the predicted ephemeris which is indicated by the red dots. We assume over this short period the differences between the ephemeris and the observation are only offsets in α, δ and time. We estimate the mean and sigma of these offsets to be:

$$\Delta\alpha = -19.322 \pm 0.017" \quad \Delta\delta = 8.454 \pm 0.018" \quad \Delta T = -9.020 \pm 1.425\text{s} \tag{1}$$

The mean part of observed offset in α, δ (around 20" of arc) is due to the fact that WMAP ephemeris provided by Dale Fink was not Astrometric Topocentric Coordinates but Apparent Topocentric Position.

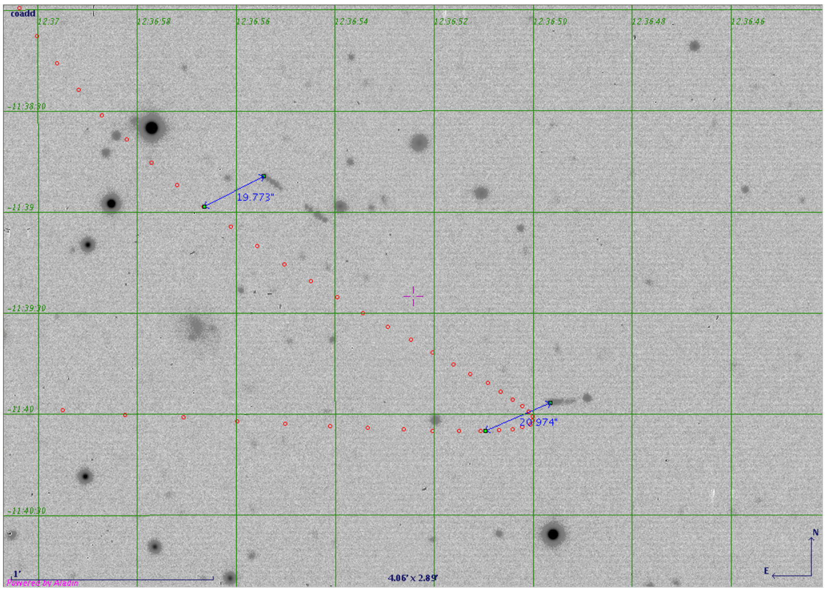

FIGURE 2: The motion of the satellite for the sequence of 20 @ 15s exposures

From this we conclude that method of observation results in a precision of better than 20 milliarcseconds.

2.2 Tracking on the satellite

We observed two images of 60 and 300 seconds with the telescope tracking set to that of the WMAP ephemeris. In figure 3 we show the 300s exposure with a zoom on the psf of WMAP. These images were reduced using the barycenter solution in SExtractor. The scatter of the residuals after the fit to the UCAC stars ($\sigma_\alpha, \sigma_\delta$) is (96,78) and (57,77) mas for the 60 and 300s exposure respectively. Part of this difference is due to the error of the UCAC stars at the epoch of the observation but for our purposes it is sufficient to see the relative errors did not improve or worsen significantly in the longer exposure.

2.3 Equatorial tracking and post observation combination of WMAP

On July 4th we observed WMAP 20 times with an exposure time of 15s and astrometrically reduced these images using 12 UCAC2 reference stars. Comparing the 20 reductions we find a mean precision (i.e. the average value of the standard error) of 22 mas with a standard deviation of 6 mas in right ascension and correspondingly 18 mas with a standard deviation of 5 mas in

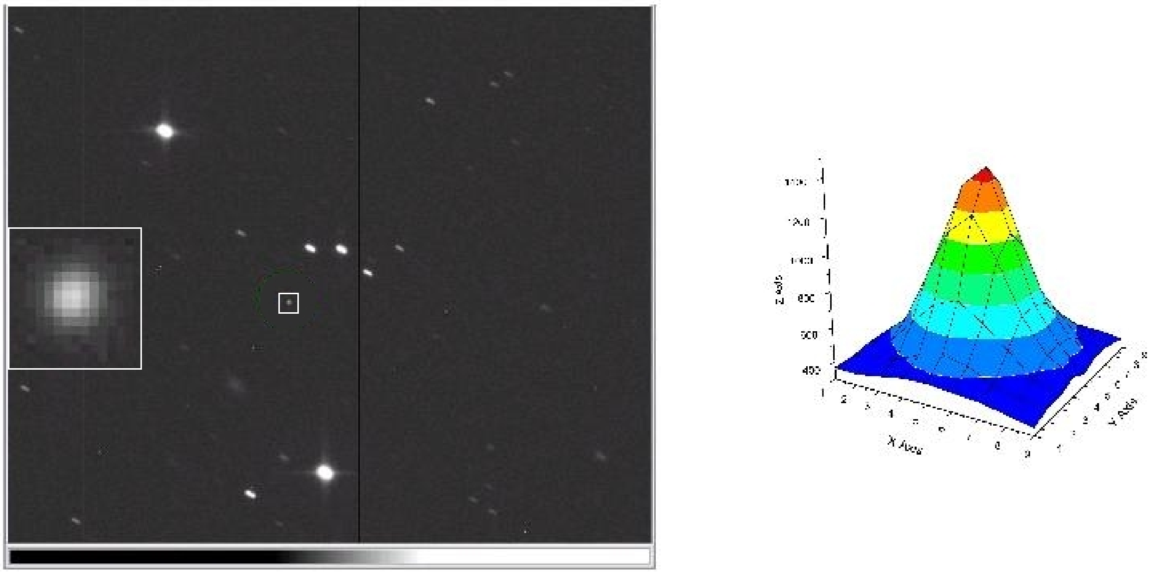

FIGURE 3: The image and reconstructed PSF for a 300s observation on the WMAP satellite tracking on as required by the ephemeris.

declination. As these are fundamentally relative positions to the UCAC they are an indication of the final error attainable when we have a Gaia catalog of much higher absolute precision. We have also combined the frames keeping the stars fixed but stacking up the pixels around the satellite position from the motion as predicted in the ephemeris, figure 4 shows the resulting psf. The formal error of this psf centroid is 0.03 pixels $\sim$ 7 mas.

3 Sky Density

To enable a definition of the minimum detector size is is useful to know the sky densities that one expects to meet during the mission. To find this we examined the variation in object density in the GSC23 Lasker et al. (2008) every .3 degrees along the the ecliptic plane. In table 3, assuming an area of 100 square arcminutes e.g. a CCD of 10'x10', we report the mean and median number of objects and stars in the listed magnitude and color ranges. The last column reports the percentage of sky without at least 10 objects in the sample selection.

The magnitudes in the GSC23 are not complete so there will be more objects per bin than reported, however, this is probably offset by the fact that not all objects are suitable for astrometric use.

One of the most difficult problems in the astrometric determination of the satellite will be the effect of differential color refraction (DCR) which is probably impossible to calibrate at the mas

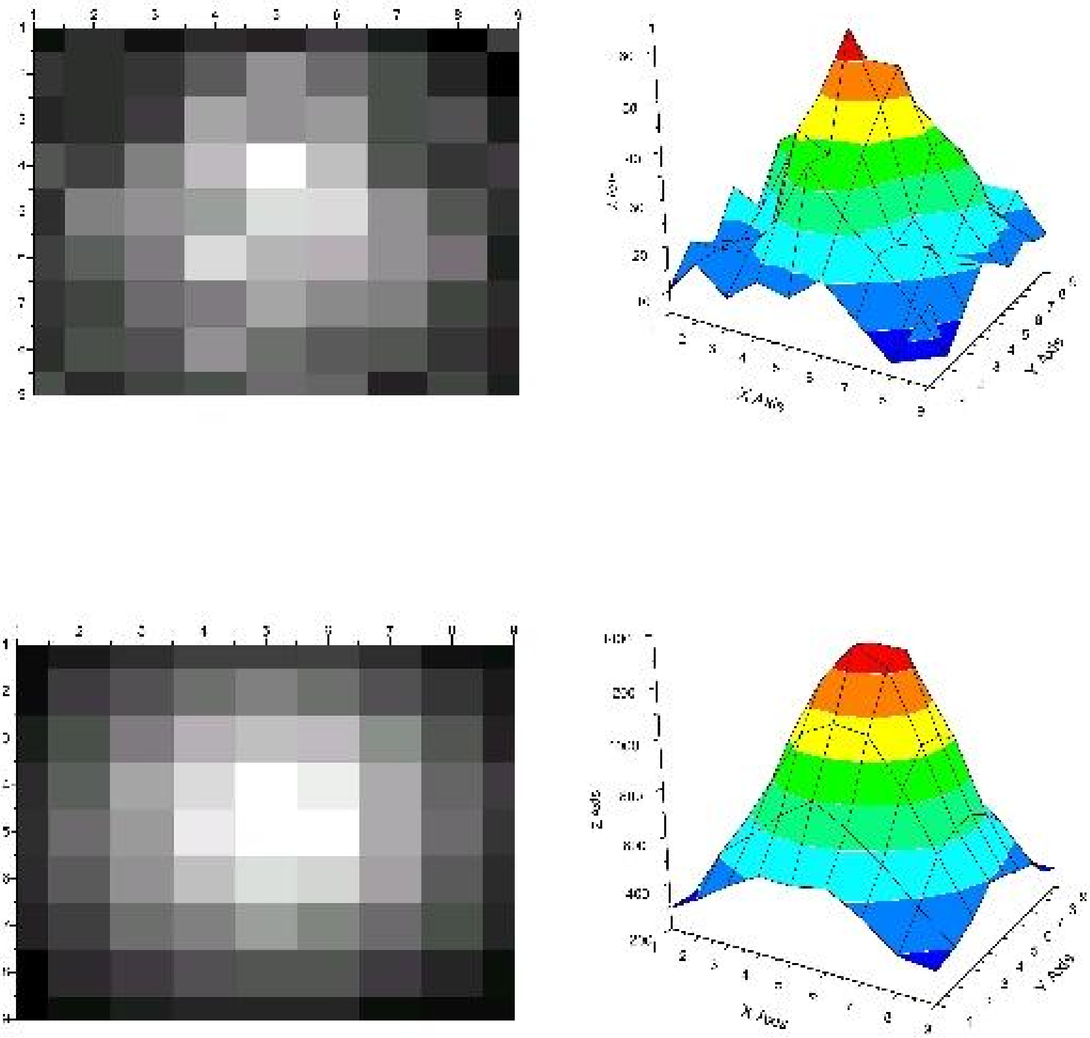

FIGURE 4: The top two frames show the image and PSF for the WMAP satellite from one 15s frame, the bottom two frames show the result of combining the 20 @ 15s satellite images including the ephemeris information.

Sample	R_F	$B_J - R_F$	Mean	Median	$\% < 10$
All Objects	...	...	530	273	0
Stars	...	...	118	76	0
Stars	16 to 20	-.2 to 0.8:	6	4	81
Stars	16 to 20	0.3 to 1.3:	23	16	18
Stars	16 to 20	0.8 to 1.8:	29	19	8
Stars	16 to 20	1.3 to 2.3:	22	18	13
Stars	16 to 20	1.8 to 2.8:	13	12	35

level. However, the better than 1 mas Gaia catalog positions at the end of the mission will be more precise than any single observation (which due to atmospheric constraints will be more like 5 mas), so we can probably independantly fit each observation for a color term. This is not presently done as the individual observations are usually more precise that the reference catalogs. Taking the rule-of-thumb requirement that the number of reference objects must be equal to the square of the parameters from the above table it is clear that we will be limited to 2nd order models with perhaps 2-3 other terms that could be functions of color, zenith distance and higher orders if required. One way to avoid the DCR problem is use objects close to the color of Gaia, what that means for density depends on the actual color of Gaia which is still not presently predicted. Based on the figures in table 3 if we can accept a large range on the color then a 10'x10' is sufficient.

4 Observation Band

All of the testing and discussion todate has been focused on the assumption that we will observe Gaia in one of the optical bands, however, given the increasing number of telescopes equiped to operate in the near infrared it is useful to consider also observing in these bands. The infrared bands (J,H,K) have a number of advantages:

- The absolute refraction is the near-IR is smaller than in the optical and varies less for a given change in color hence the differential refraction is much smaller than the optical bands.
- The seeing is smaller. The seeing is J is approximately 90% of that in I. Since all ground based observations in these bands on telescopes over 1m are seeing limited the centroiding should improve accordingly, providing, we do not under sample, e.g. the pixel is less that 1/3 of the seeing.
- The readout time and noise characteristics in the IR is such that the normal observational procedure is to make many short exposures and co-add them. Given our

success with the method of rebuilding the satellite PSF from multiple images including the ephemeris information this seems to be an optimal approach with these observations.

- The proposed ground based tracking of Gaia must be programmed to be via service and robotic observations. Many of the medium telescopes and detector systems that will be stable for the period 2012-2018 with service/robotic observations are being dedicated to IR observations. This is because the exploitation of the IR waveband is younger than that of the visible and therefore more supported.
- A full moon is less of a problem in the infrared bands.

As a result of item 1 we can enlarge the reference star window and hence accept detectors with smaller dimensions. The smaller dimensions also support the relative precision requirement as precision is directly proportional to the angular separations being measured (Lindegren 1980; Han 1989). The remaining question with regard to observations in the IR is what is the predicted magnitude of Gaia in these bands for which we await input from industry.

The IR also has a number of dis-advantages:

- The detectors are expensive and in general smaller than the optical counterparts.
- Access is more competitive.
- The background is higher decreasing the S/N.
- There are very few optimised for astrometry.
- The initial image reduction procedures are usually much more complex because of the larger number of noise and background sources.

5 Conclusion and Future

We have confirmed the technical feasibility of using 1-2m class telescopes for the determination of a satellite position at the sub-20 mas level. We have tested the possibilities for different tracking procedures and feel it is particularly important to continue testing especially in the infrared and using different tracking techniques on other telescopes.

The data processing procedures combining daily observations from many telescope and detector systems will be paticularly arduous. In particular the current software being used for the astrometric reduction these frames is not open source and for astrometry on varied telescopes we require the ability to modify the code as needed. We propose to produce a suite of reduction programs that are open source and flexible enough to meet these varied demands. The SYRTE/Paris Observatory will be coordinating this effort.

We propose that a trail run of 6 months observations a suitable target such as an asteroid be organized before Gaia is launched to ensure that from the beginning the ground based tracking campaign is ready to start.

6 References

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Appendix A: Observations carried out 04/04/2008

Image UT	trck	bin	Tex	Flt	AirM	Seeing
04_02_56.733	N	2x2	300	V		
04_02_13.111	N	1x1	150	V		
04_12_09.281	N	1x1	15	V	1.051	0.65
04_13_33.893	N	1x1	15	V	1.051	0.65
04_15_01.456	N	1x1	15	V	1.050	0.65
04_16_25.556	N	1x1	15	V	1.050	0.73
04_18_00.961	N	1x1	15	V	1.050	0.73
04_27_31.412	N	1x1	15	R	1.048	0.80
04_28_58.084	N	1x1	15	R	1.048	0.80
04_31_28.399	N	1x1	15	R	1.049	0.80
04_32_55.061	N	1x1	15	R	1.049	0.80
04_34_27.606	N	1x1	15	R	1.049	0.80
07_30_42.293	N	1x1	150	V	1.434	0.86
07_43_56.907	N	1x1	15	V	1.511	0.99
07_45_39.495	N	1x1	15	V	1.522	0.99
07_47_09.618	N	1x1	15	V	1.532	0.98
07_48_33.209	N	1x1	15	V	1.541	0.98
07_49_59.811	N	1x1	15	V	1.551	0.98
07_53_24.736	N	1x1	30	V	1.575	0.98
07_55_06.254	N	1x1	30	V	1.588	0.98
07_56_47.651	N	1x1	30	V	1.600	1.00
07_58_27.628	N	1x1	30	V	1.613	1.00
08_00_04.784	N	1x1	30	V	1.625	1.00
05_07_43.552	N	1x1	30	V	1.061	0.68
05_09_40.786	N	1x1	30	V	1.062	0.68
05_11_38.739	N	1x1	60	V	1.064	0.68
05_14_00.962	N	1x1	60	V	1.066	0.68
05_16_21.594	N	1x1	60	V	1.067	0.68
05_19_43.049	N	2x2	60	V	1.068	0.68
05_24_19.260	Y	1x1	60	V	1.075	0.68
05_41_37.854	Y	1x1	300	V	1.096	1.00