

Repeat of the empirical determination of the delay in the between the time the LMI shutter is commanded to open, and the time it actually opens.

(v. 20210919)

Reduction and write up by S. Levine

Images taken by B. Shafransky, night plan by T. Ellsworth-Bowers

Repeat requested by N. Moskovitz

The spreadsheet was updated and simplified for this version. See Offset comp 20210918b for the reduction. One item of note for the reducer. These satellites move quickly enough that the arcs on sky are not well approximated by a straight line. As such, it pays to reduce against a finer grained ephemeris than is likely to be used at the telescope. The 4 images from 20210918b were done against 15second, 1minute and 4minute interval ephemerides see Offset comp page). The mean results between the shorter two and the 4minute case differ by more than 1 RMS. The 15sec and 1minute results are similar within the RMS. Nicer to reduce against the 15second, but 1minute is acceptable.

The time difference is computed as follows:

- a) reduce image as normal, through doing a proper astrometric solution of the frame.
- b) measure the RA, Dec position of the satellite streak center
  - if the streak is short enough, an object detection code can probably find the streak center directly. E.g. SExtractor treats a short streak as an elongated celestial object. If it is too long for that, the center can be determined by measuring the streak ends and finding the mid-point.
- c) Interpolate between the bracketing ephemeris values in RA (Dec) to find the nominal time that predicts that RA (Dec).:
  - $T_{mid,RA} = Ephem_0 + (RA_{sat} - RA_0) / (RA_1 - RA_0) * (Ephem_1 - Ephem_0)$
  - $T_{mid,Dec} = Ephem_0 + (Dec_{sat} - Dec_0) / (Dec_1 - Dec_0) * (Ephem_1 - Ephem_0)$
  - As noted above, the granularity of the reduction ephemeris probably needs to be finer than that used for taking the observations.
- d) The mid-time differences relative to the listed UTCSTART and UTCEND are:
  - $dT_{RA,Dec,start} = T_{mid,RA,Dec} - EXPTIME/2 - UTCSTART$
  - $dT_{RA,Dec,end} = T_{mid,RA,Dec} + EXPTIME/2 - UTCEND$

See the 2018 Intro for the results of the prior test (attached at the end).

The next sheet is a printout of the spreadsheet used for the reduction. The summary is that:

- 1) Formal uncertainty on the measured time offsets are an underestimate of the true variation. The shutter throw time alone means the mid-time varies across the frame systematically by at least 0.1second (added as the systematic uncertainty below).
- 2) The shutter opens 2.06 +/- 0.02 (ran) +/- 0.1 (sys) seconds later than the UTCSTART in the image header.
- 3) The shutter closes 0.18 +/- 0.02 (ran) +/- 0.1 (sys) seconds earlier than the UTCEND in the image header.

The offsets have formally shifted by 0.01sec, which is I think well within the uncertainties.

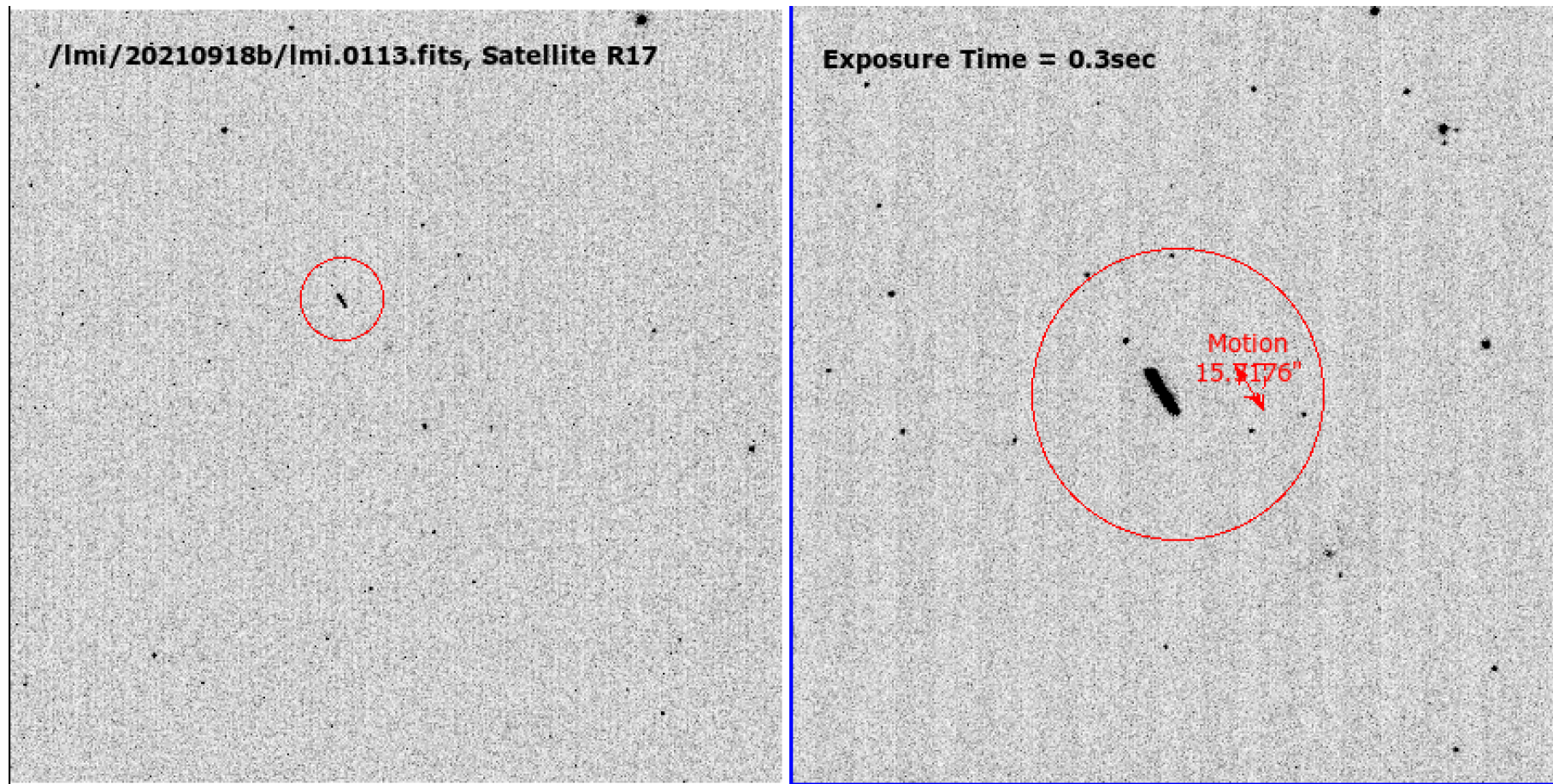
As such, I am retaining the previous recommendation:

Exposure times should be computed as:

- 1) Start time = UTCSTART + 2.05sec
- 2) End time = UTCEND - 0.19sec
- 3) Mid-time = UTCSTART + 2.05 + EXPTIME/2 or
- 4) Mid-time = [(UTCSTART + 2.05) + (UTCEND-0.19)] / 2

Useful web site: [https://www.projectpluto.com/gps\\_expl.htm](https://www.projectpluto.com/gps_expl.htm)

The site provides explanatory materials and an ephemeris calculator.



Sample image from 20210918 UT showing a 0.3second exposure with the satellite R17. Left: full LMI image; Right: zoom of the region around the satellite. The streak length is roughly 15.3arcseconds, giving a rate of 51arcsec/second on the sky.

For image lmi.0113.fits, a line cut along the streak has length 12.4 arcsec from about streak half height to streak half height. The R17 ephemeris says the rate at the should have been 40.67 arcsec/sec. For a 0.3sec exposure, that predicts a 12.2arcsec streak. The agreement, especially considering the crude measurement seems to imply that the shutter open duration is still correct.

Images are in /mi/20210918b/

20210918b - 15sec ephemeris interval

ImageID	UTCSTART	UTCEND	EXPTIME	ObjRA	ObjDec	EphemT0	T0_RA	T0_Dec	EphemT1	T1_RA	T1_Dec	RA_MidTime	DecMidTime	RA_Start_Offset	Dec_Start_Offset	RA_End_Offset	Dec_End_Offset	Start_Offset	End_Offset
0113	8:43:00.410	8:43:02.950	0:00:00.300	2:40:58.832	41:14:23.533	8:43:00.000	2:40:53.853	41:12:52.266	8:43:15.000	2:41:22.082	41:21:31.942	8:43:02.646	8:43:02.634	0:00:02.086	0:00:02.074	-0:00:00.154	-0:00:00.166	0:00:02.080	-0:00:00.160
0114	8:47:00.460	8:47:03.100	0:00:00.400	2:48:46.923	43:31:49.273	8:47:00.000	2:48:41.427	43:30:17.323	8:47:15.000	2:49:11.824	43:38:47.443	8:47:02.712	8:47:02.704	0:00:02.052	0:00:02.044	-0:00:00.188	-0:00:00.196	0:00:02.048	-0:00:00.192
0115	8:51:00.340	8:51:03.080	0:00:00.500	2:57:11.570	45:46:27.325	8:51:00.000	2:57:05.738	45:44:58.281	8:51:15.000	2:57:38.583	45:53:17.321	8:51:02.663	8:51:02.676	0:00:02.073	0:00:02.086	-0:00:00.167	-0:00:00.154	0:00:02.080	-0:00:00.160
0116	8:55:00.490	8:55:03.330	0:00:00.600	3:06:18.275	47:58:01.300	8:55:00.000	3:06:11.544	47:56:29.430	8:55:15.000	3:06:47.153	48:04:35.681	8:55:02.835	8:55:02.834	0:00:02.045	0:00:02.044	-0:00:00.195	-0:00:00.196	0:00:02.045	-0:00:00.195
Mean Values														0:00:02.064	0:00:02.062	-0:00:00.176	-0:00:00.178	0:00:02.063	-0:00:00.177
RMS																		0:00:00.019	0:00:00.019

20210918b - 1 minute ephemeris interval

ImageID	UTCSTART	UTCEND	EXPTIME	ObjRA	ObjDec	EphemT0	T0_RA	T0_Dec	EphemT1	T1_RA	T1_Dec	RA_MidTime	DecMidTime	RA_Start_Offset	Dec_Start_Offset	RA_End_Offset	Dec_End_Offset	Start_Offset	End_Offset
0113	8:43:00.410	8:43:02.950	0:00:00.300	2:40:58.832	41:14:23.533	8:43:00.000	2:40:53.853	41:12:52.266	8:44:00.000	2:42:47.542	41:47:27.615	8:43:02.628	8:43:02.639	0:00:02.068	0:00:02.079	-0:00:00.172	-0:00:00.161	0:00:02.073	-0:00:00.167
0114	8:47:00.460	8:47:03.100	0:00:00.400	2:48:46.923	43:31:49.273	8:47:00.000	2:48:41.427	43:30:17.323	8:48:00.000	2:50:43.885	44:04:13.901	8:47:02.693	8:47:02.709	0:00:02.033	0:00:02.049	-0:00:00.207	-0:00:00.191	0:00:02.041	-0:00:00.199
0115	8:51:00.340	8:51:03.080	0:00:00.500	2:57:11.570	45:46:27.325	8:51:00.000	2:57:05.738	45:44:58.281	8:52:00.000	2:59:18.101	46:18:09.933	8:51:02.644	8:51:02.683	0:00:02.054	0:00:02.093	-0:00:00.186	-0:00:00.147	0:00:02.073	-0:00:00.167
0116	8:55:00.490	8:55:03.330	0:00:00.600	3:06:18.275	47:58:01.300	8:55:00.000	3:06:11.544	47:56:29.430	8:56:00.000	3:08:35.091	48:28:49.244	8:55:02.814	8:55:02.842	0:00:02.024	0:00:02.052	-0:00:00.216	-0:00:00.188	0:00:02.038	-0:00:00.202
Mean Values														0:00:02.044	0:00:02.068	-0:00:00.196	-0:00:00.172	0:00:02.056	-0:00:00.184
RMS																		0:00:00.020	0:00:00.020

20210918b - 4 minute ephemeris interval

ImageID	UTCSTART	UTCEND	EXPTIME	ObjRA	ObjDec	EphemT0	T0_RA	T0_Dec	EphemT1	T1_RA	T1_Dec	RA_MidTime	DecMidTime	RA_Start_Offset	Dec_Start_Offset	RA_End_Offset	Dec_End_Offset	Start_Offset	End_Offset
0113	8:43:00.410	8:43:02.950	0:00:00.300	2:40:58.832	41:14:23.533	8:43:00.000	2:40:53.853	41:12:52.266	8:47:00.000	2:48:41.427	43:30:17.323	8:43:02.556	8:43:02.657	0:00:01.996	0:00:02.097	-0:00:00.244	-0:00:00.143	0:00:02.046	-0:00:00.194
0114	8:47:00.460	8:47:03.100	0:00:00.400	2:48:46.923	43:31:49.273	8:47:00.000	2:48:41.427	43:30:17.323	8:51:00.000	2:57:05.738	45:44:58.281	8:47:02.615	8:47:02.731	0:00:01.955	0:00:02.071	-0:00:00.285	-0:00:00.169	0:00:02.013	-0:00:00.227
0115	8:51:00.340	8:51:03.080	0:00:00.500	2:57:11.570	45:46:27.325	8:51:00.000	2:57:05.738	45:44:58.281	8:55:00.000	3:06:11.544	47:56:29.430	8:51:02.564	8:51:02.708	0:00:01.974	0:00:02.118	-0:00:00.266	-0:00:00.122	0:00:02.046	-0:00:00.194
0116	8:55:00.490	8:55:03.330	0:00:00.600	3:06:18.275	47:58:01.300	8:55:00.000	3:06:11.544	47:56:29.430	8:59:00.000	3:16:04.183	50:04:21.817	8:55:02.726	8:55:02.874	0:00:01.936	0:00:02.084	-0:00:00.304	-0:00:00.156	0:00:02.010	-0:00:00.230
Mean Values														0:00:01.965	0:00:02.092	-0:00:00.275	-0:00:00.148	0:00:02.029	-0:00:00.211
RMS																		0:00:00.020	0:00:00.020

Check using last times (20180530) data

ImageID	UTCSTART	UTCEND	EXPTIME	ObjRA	ObjDec	EphemT0	T0_RA	T0_Dec	EphemT1	T1_RA	T1_Dec	RA_MidTime	DecMidTime	RA_Start_Offset	Dec_Start_Offset	RA_End_Offset	Dec_End_Offset
0140	3:32:02.340	3:32:04.770	0:00:00.200	12:01:10.108	15:17:51.266	3:32:00.000	12:01:05.557	15:15:05.481	3:33:00.000	12:02:06.907	15:52:10.408	3:32:04.451	3:32:04.471	0:00:02.011	0:00:02.031	-0:00:00.219	-0:00:00.199
Mean Values														0:00:02.011	0:00:02.031	-0:00:00.219	-0:00:00.199

Empirical determination of the delay in the between the time the LMI shutter is commanded to open, and the time it actually opens.  
(v. 20181205a)

Reduction and write up by S. Levine  
Images taken by T. Pugh and J. Sanborn  
Idea originally proposed by N. Moskovitz

We have known for a while that there was a delay between the time the user commands the start of an exposure and the time when the shutter actually triggers. The delay has been presumed to be on the order of a few seconds. For most applications, this was not an issue. However, for astrometry of near Earth objects (e.g. NEOs, comets, etc), an uncertainty in the exposure mid-time of a second can translate into unacceptably large positional uncertainties.

To assess this uncertainty, we took short images of low Earth orbiting satellites with well known ephemerides. Then, we compared the measured satellite positions to the predicted positions and derived the image mid-time.

We also checked that the exposure times were as requested by measuring streaked stars on untracked sky flat.

The attached pages are a printout of the spreadsheet used for the reduction. The simple summary is that:

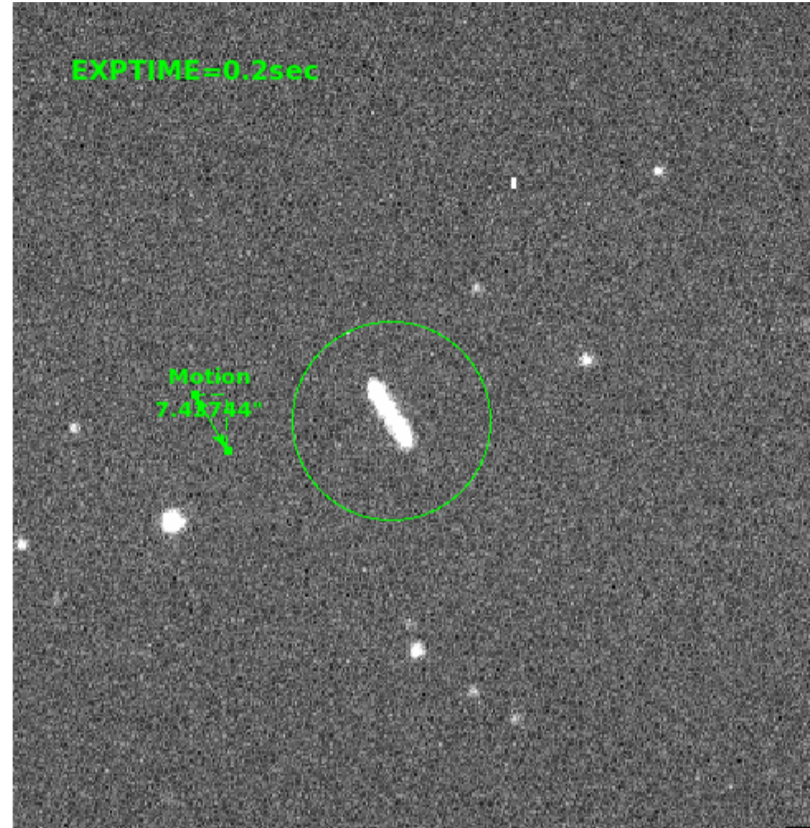
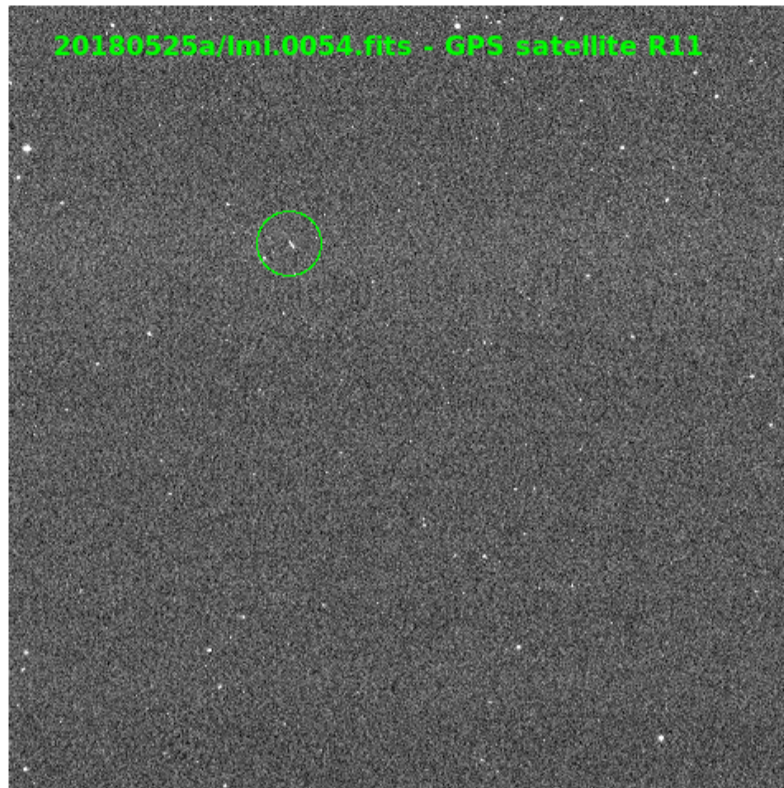
- 1) The exposure times are as recorded to within a few hundredths of a second, based on the star streaks.
- 2) The shutter throw time in each direction is between roughly 0.1 and 0.2 seconds, meaning that there is also a temporal gradient across all the images.
- 3) Formal uncertainty on the measured time offsets are an underestimate of the true variation. The shutter throw time alone means the mid-time varies across the frame systematically by at least 0.1second (added as the systematic uncertainty below).
- 4) The shutter opens 2.05 +/- 0.06 (ran) +/- 0.1 (sys) seconds later than the UTCSTART in the image header.
- 5) The shutter closes 0.19 +/- 0.06 (ran) +/- 0.1 (sys) seconds earlier than the UTCEND in the image header.

Exposure times should be computed as:

- 1) Start time = UTCSTART + 2.05sec
- 2) End time = UTCEND - 0.19sec
- 3) Mid-time = UTCSTART + 2.05 + EXPTIME/2 or
- 4) Mid-time = [(UTCSTART + 2.05) + (UTCEND-0.19)] / 2

Useful web site: [https://www.projectpluto.com/gps\\_expl.htm](https://www.projectpluto.com/gps_expl.htm)

The site provides explanatory materials and an ephemeris calculator.



Sample image from 20180525 UT showing a 0.2second exposure with the satellite R11. Left: full LMI image; Right: zoom of the region around the satellite

Summary: The LMI shutter opens 2.05 seconds later than the recorded UTCSTART time,  
and closes 0.19 seconds before the UTCEND time.

Computed Shutter Offset Time based on GPS satellite observation on 2018-05-30 UT @ DCT with LMI

	FITS UTCSTART	FITS UTCEND	FITS EXPTIME	Start Offset	End Offset	Computed START	Computed END
180530/lmi.0040	3:32:02.340	3:32:04.770	0:00:00.200	0:00:02.021	-0:00:00.209	3:32:04.361	3:32:04.561
180530/lmi.0042	3:36:01.640	3:36:04.080	0:00:00.200	0:00:02.018	-0:00:00.222	3:36:03.658	3:36:03.858
180530/lmi.0045	3:50:01.500	3:50:03.930	0:00:00.200	0:00:02.052	-0:00:00.178	3:50:03.552	3:50:03.752
180530/lmi.0050	4:18:01.470	4:18:03.910	0:00:00.200	0:00:02.068	-0:00:00.172	4:18:03.538	4:18:03.738
180525/lmi.0054	9:30:02.500	9:30:04.930	0:00:00.200	0:00:01.971	-0:00:00.259	9:30:04.471	9:30:04.671
180525/lmi.0081	9:45:07.300	9:45:10.040	0:00:00.500	0:00:02.151	-0:00:00.089	9:45:09.451	9:45:09.951
Mean:				0:00:02.047	-0:00:00.188		
Sample RMS:				0:00:00.061	0:00:00.058		

Computing Shutter Offset Time from GPS Satellite Observation - Sat: R04, lmg: 20180530/lmi.0040

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180530/lmi.0040							
Ephem T0	12:01:05.557	15:15:05.481	180:16:23.349	15:15:05.481	3:32:00.000		
Ephem T1	12:02:06.907	15:52:10.408	180:31:43.600	15:52:10.408	3:33:00.000		
Object			180.2921184	15.2975740	3h 32m 4s 452ms	3h 32m 4s 471ms	
			Tmid - EXPTIME/2 - UTCSTART:		0:00:02.012	0:00:02.031	0:00:02.021
	FITS HDR		Tmid + EXPTIME/2 - UTCEND:		-0:00:00.218	-0:00:00.199	-0:00:00.209
UTCSTART	3:32:02.340				3:32:04.352	3:32:04.371	3:32:04.361
UTCEND	3:32:04.770				3:32:04.552	3:32:04.571	3:32:04.561
EXPTIME	0:00:00.200						
						FILL IN BOXES WITH HEAVY OUTLINE	
180530/lmi.0040	3:32:02.340	3:32:04.770	0:00:00.200	0:00:02.021	-0:00:00.209	3:32:04.361	3:32:04.561

Computing Shutter Offset Time from GPS Satellite Observation - Sat: R04, lmg: 20180530/lmi.0042

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180530/lmi.0042							
Ephem T0	12:05:13.699	17:43:28.415	181:18:25.481	17:43:28.415	3:36:00.000		
Ephem T1	12:06:16.931	18:20:35.073	181:34:13.966	18:20:35.073	3:37:00.000		
Object			181.3235462	17.7633879	3h 36m 3s 750ms	3h 36m 3s 767ms	
			Tmid - EXPTIME/2 - UTCSTART:		0:00:02.010	0:00:02.027	0:00:02.018
	FITS HDR		Tmid + EXPTIME/2 - UTCEND:		-0:00:00.230	-0:00:00.213	-0:00:00.222
UTCSTART	3:36:01.640				3:36:03.650	3:36:03.667	3:36:03.658
UTCEND	3:36:04.080				3:36:03.850	3:36:03.867	3:36:03.858
EXPTIME	0:00:00.200						
						FILL IN BOXES WITH HEAVY OUTLINE	
180530/lmi.0042	3:36:01.640	3:36:04.080	0:00:00.200	0:00:02.018	-0:00:00.222	3:36:03.658	3:36:03.858

Computing Shutter Offset Time from GPS Satellite Observation - Sat: R04, Img: 20180530/Imi.0045

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180530/Imi.0045							
Ephem T0	12:20:52.509	26:22:22.193	185:13:07.635	26:22:22.193	3:50:00.000		
Ephem T1	12:22:04.711	26:59:17.773	185:31:10.664	26:59:17.773	3:51:00.000		
Object			185.2370481	26.4103937	3h 50m 3s 642ms	3h 50m 3s 662ms	
			<b>Tmid - EXPTIME/2 - UTCSTART:</b>		0:00:02.042	0:00:02.062	0:00:02.052
	<b>FITS HDR</b>		<b>Tmid + EXPTIME/2 - UTCEND:</b>		-0:00:00.188	-0:00:00.168	-0:00:00.178
UTCSTART	3:50:01.500				3:50:03.542	3:50:03.562	3:50:03.552
UTCEND	3:50:03.930				3:50:03.742	3:50:03.762	3:50:03.752
EXPTIME	0:00:00.200						
						FILL IN BOXES WITH HEAVY OUTLINE	
180530/Imi.0045	3:50:01.500	3:50:03.930	0:00:00.200	0:00:02.052	-0:00:00.178	3:50:03.552	3:50:03.752

Computing Shutter Offset Time from GPS Satellite Observation - Sat: R04, Img: 20180530/Imi.0050

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180530/Imi.0050							
Ephem T0	13:01:27.754	43:14:27.185	195:21:56.314	43:14:27.185	4:18:00.000		
Ephem T1	13:03:16.224	43:49:17.690	195:49:03.361	43:49:17.690	4:19:00.000		
Object			195.3928521	43.2763420	4h 18m 3s 612ms	4h 18m 3s 664ms	
			<b>Tmid - EXPTIME/2 - UTCSTART:</b>		0:00:02.042	0:00:02.094	0:00:02.068
	<b>FITS HDR</b>		<b>Tmid + EXPTIME/2 - UTCEND:</b>		-0:00:00.198	-0:00:00.146	-0:00:00.172
UTCSTART	4:18:01.470				4:18:03.512	4:18:03.564	4:18:03.538
UTCEND	4:18:03.910				4:18:03.712	4:18:03.764	4:18:03.738
EXPTIME	0:00:00.200						
						FILL IN BOXES WITH HEAVY OUTLINE	
180530/Imi.0050	4:18:01.470	4:18:03.910	0:00:00.200	0:00:02.068	-0:00:00.172	4:18:03.538	4:18:03.738

Computing Shutter Offset Time from GPS Satellite Observation - Sat: R11, Img: 20180525/lmi.0054

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180525/lmi.0054							
Ephem T0	21:25:51.400	30:17:38.282	321:27:51.000	30:17:38.282	9:30:00.000		
Ephem T1	21:34:17.245	33:05:03.933	323:34:18.675	33:05:03.933	9:35:00.000		
Object			321:29:44.642	30:20:13.976	9:30:04.493	9:30:04.650	
			<b>Tmid - EXPTIME/2 - UTCSTART:</b>		0:00:01.893	0:00:02.050	0:00:01.971
	<b>FITS HDR</b>		<b>Tmid + EXPTIME/2 - UTCEND:</b>		-0:00:00.337	-0:00:00.180	-0:00:00.259
UTCSTART	9:30:02.500				9:30:04.393	9:30:04.550	9:30:04.471
UTCEND	9:30:04.930				9:30:04.593	9:30:04.750	9:30:04.671
EXPTIME	0:00:00.200						
						FILL IN BOXES WITH HEAVY OUTLINE	
180525/lmi.0054	9:30:02.500	9:30:04.930	0:00:00.200	0:00:01.971	-0:00:00.259	9:30:04.471	9:30:04.671

Computing Shutter Offset Time from GPS Satellite Observation - Sat: G10, Img: 20180525/lmi.0081

Frame	RA (HMS)	Dec (DMS)	RA(deg)	Dec (deg)	Time (HMS) / Tmid(RA)	Tmid(Dec)	Mean Offset & Updated Times
180525/lmi.0081							
Ephem T0	22:05:18.480	-1:57:03.698	331:19:37.200	-1:57:03.698	9:45:00.000		
Ephem T1	22:11:06.325	-4:18:19.901	332:46:34.875	-4:18:19.901	9:50:00.000		
Object			331:22:25.632	-2:01:38.250	9:45:09.684	9:45:09.717	
			<b>Tmid - EXPTIME/2 - UTCSTART:</b>		0:00:02.134	0:00:02.167	0:00:02.151
	<b>FITS HDR</b>		<b>Tmid + EXPTIME/2 - UTCEND:</b>		-0:00:00.106	-0:00:00.073	-0:00:00.089
UTCSTART	9:45:07.300				9:45:09.434	9:45:09.467	9:45:09.451
UTCEND	9:45:10.040				9:45:09.934	9:45:09.967	9:45:09.951
EXPTIME	0:00:00.500						
						FILL IN BOXES WITH HEAVY OUTLINE	
180525/lmi.0081	9:45:07.300	9:45:10.040	0:00:00.500	0:00:02.151	-0:00:00.089	9:45:09.451	9:45:09.951