First results of a Raspberry Pi based meteor camera system

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We present first orbital solution of a meteor estimated completely using open-source methods and software running on a Raspberry Pi single-board computer. Astrometry methods and tools are described in detail, and we find that our results compare well to independent Croatian Meteor Network observations and UFOOrbit trajectory estimation results. We explore a CMOS alternative to the recently discontinued Sony CCD low-light CCD sensors. Sensitivity, linearity of the sensor, and the quality of photometry are discussed.

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1 Introduction

Following the development and wide availability of low-cost low-light security cameras, their potential for meteor observation was quickly realized by amateur astronomers (Gural & Segon, 2009; Samuels et al., 2014). Zubović et al. (2015) were the first to offer an alternative to using personal computers for automatic meteor data acquisition and processing by demonstrating that single-board computers such as the Raspberry Pi 2[a] are up to the task as well. Vida et al. (2016) presented open-source meteor detection software designed for single-board computers, which can run on personal computers as well, and laid out the roadmap towards a network of low-cost meteor stations. Early developments were documented as part of the Asteria Network project[b] which was organized for the 2015 Hackaday Prize. Subsequently, the development continued and the code remained available on GitHub[c]. In the end we have adopted the name RMS (Raspberry Pi Meteor Station) for the software, although the code runs fine on personal computers as well.

The main idea behind the project is to provide a reliable, low-cost replacement for existing meteor observation systems and offer improvements on proprietary and antiquated meteor detection software commonly used today. By making our code completely transparent and data acquired by the systems open, we hope to motivate the creation an international community of meteor astronomers, a global meteor network with large sky coverage and standardized methodology. We aim to develop modular systems based on moderate field-of-view cameras which can be deployed in a variety of configurations, from single camera to multi-camera all-sky arrangements, satisfying needs of most amateur astronomers. The software pipeline will be designed to provide near real-time reporting of meteor radiants and orbits which will be available to the general public, while the main goal is to have enough stations around the globe to acquire at least 1000 optical meteor orbits a night.

A large sky coverage is essential for answering fundamental questions in meteor science. Strong meteor shower outbursts are often of very short duration and are geographically localized, for example the 2011 February η Draconid outburst (Jenniskens & Gural, 2011), 2014 Camelopardalid outburst (Campbell-Brown et al., 2016), and the 2015 Taurid outburst (Spurny et al., 2017). Their short duration and localization make their observation precarious, creating a possibility of not optically observing an outburst at all due to unfavourable weather conditions. For example, the 2011 October Draconid outburst (Ye et al., 2013a) lasted only $\sim$ 4 hours, but was well observed visually both from the ground (Molau & Barentsen, 2014) and the air (Vaubaillon et al., 2015; Koten et al., 2014) due to previous predictions by Vaubaillon et al. (2011). On the other hand, the 2012 Draconid meteor storm ($\mathrm{ZHR_{max}} \approx 9000 \pm 1000$ in radar sizes) was only noticed by chance by Ye et al. (2013b), while only real-time optical data was provided by visual observers on another continent, albeit with a much lower ZHR. The outburst was poorly observed optically – it was not observed by CAMS (Jenniskens et al., 2016), Toth et al. (2014) observed 28 Draconids but gave no details about the radiants, and Molau et al. (2013) reported a 90 minute peak of activity based on single-station observations. Ye et al. (2013b) show radiants with high dispersion, which is purely an observation bias due to low precision of radar measurements, while their dynamical simulations show very tight radiants. If high precision optical data was available, the simulations could have been better constrained and predictions of future outbursts made more reliable. Furthermore, a wide coverage may reduce observational biases for meteor shower flux statistics as well (Blaauw et al., 2016; Campbell-Brown & Braid, 2011). Finally, meteor showers with very low flux can possibly be discovered simply due to the larger number statistics.

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[a]Raspberry Pi 2 – `https://www.raspberrypi.org/products/raspberry-pi-2-model-b/` (Accessed December 28, 2017)
[b]Hackaday.io – Asteria network `https://hackaday.io/project/6811-asteria-network`, (Accessed December 28, 2017)
[c]RMS source code on GitHub, `https://github.com/CroatianMeteorNetwork/RMS`, (Accessed December 28, 2017)

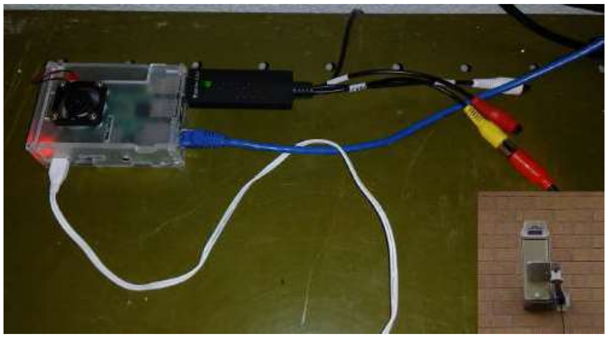

Figure 1 – Raspberry Pi system at Elginfield.

A dense global meteor network would result in an increase of instrumentally observed meteorite falls – currently only about 30 meteorites have known orbits (Spurny, 2015). Also, more data would be collected on very rare simultaneous meteors which fragment before entering the atmosphere (Koten et al., 2017).

Finally, atmospheric phenomena like sprites and blue jets can be observed with such systems, enabling their localization and connection to discharges in the lower atmosphere (Wescott et al., 2001), as well as meteor-triggered high-atmosphere discharges (Suszcynsky et al., 1999).

In this work we present the current progress of both hardware and software development, first concrete results and orbits, and plans for expansion of the network in the near future.

2 Current software and hardware status

At the time of publication of this article, systems running our code were operational in Canada, Croatia, France and the Netherlands, while testing is being conducted in Brazil, Germany and Korea. The first permanent meteor station running our software was deployed in June 2017 at Elginfield Observatory, north of London, Ontario (Canada). The system consists of an analog Sony Effio 673 CCD camera, EasyCap video digitizer, and a Raspberry Pi 3 single-board computer (Figure 1). This system was used as a test bed for new features and stability tests. Detailed instructions on how to build such a system were published on the Instructables website[d]. At the time of writing of this article, the system has reliably captured meteors for months without interruption or errors, requiring no external intervention. Figure 2 shows the stack of images of 54 meteors detected in one night in late July 2017.

3 Updated processing pipeline

The data processing pipeline has been updated since the work presented in Vida et al. (2016) to include automatic astrometric calibration, data management and uploading calibrated meteor detections to a central server located at the University of Western Ontario. Figure 3

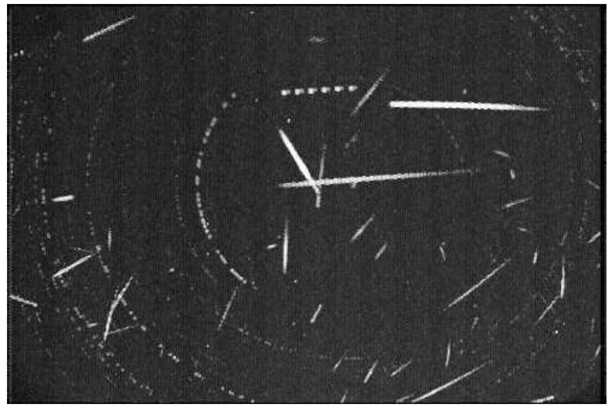

Figure 2 – 54 meteors detected on the night of July 29^{th} to 30^{th}, 2017 with the Elginfield system.

shows a diagram of the updated pipeline. With properly configured software, it will wait until sundown (when the Sun is 5.5° below the horizon) to start capturing. Two memory buffers, each the size of 256 video frames, are initialized and the video stream is alternated between them. When the first block of 256 is full, Four-frame Temporal Pixel (FTP) compression (Gural, 2011) is performed on them, after which real-time fireball detection is performed as well. Due to compression artifacts produced by the FTP compression on very bright events it is preferable to extract and store raw video frames of such bright events for later analysis. This procedure is described in more detail in (Vida et al., 2016).

All FTP compressed files are put on a queue from which they are relayed to threads running star extraction and meteor detection. As these tasks are more computationally intensive, they are not performed in real time and are left to run after sunrise. Only one detection thread is running during video capture, while two more are spawned after it ends at sunrise.

The detection often finishes within one hour after sunrise, after which automatic recalibration of astrometric parameters is performed. In summary, 5 parameters define the basic astrometric solution (centre of the field of view): reference Julian date JD_{ref}, equatorial coordinates of the field-of-view (FOV) centre α_{ref} and δ_{ref} at JD_{ref}, pixel scale, and reference position angle. The distortion is estimated using 3^{rd} order polynomials with an added radial distortion term (12 additional parameters, for details see Vida et al. (2016)). The parameter refinement is stopped upon finding a set of astrometric parameters which produce the smallest average residual between the predicted and the observed positions of stars, or it is stopped when the average residual becomes smaller than 1/3 of a pixel – this precision is achieved most nights. We also consider the number of matched stars as an indicator of the quality of the fit, thus we have defined the cost function for minimization as:

$$C = \frac{\bar{d}^2}{\sqrt{N_{matched} + 1}} \quad (1)$$

[d]Building a Raspberry Pi meteor station: `http://www.instructables.com/id/Raspberry-Pi-Meteor-Station/` (Accessed December 30, 2017)

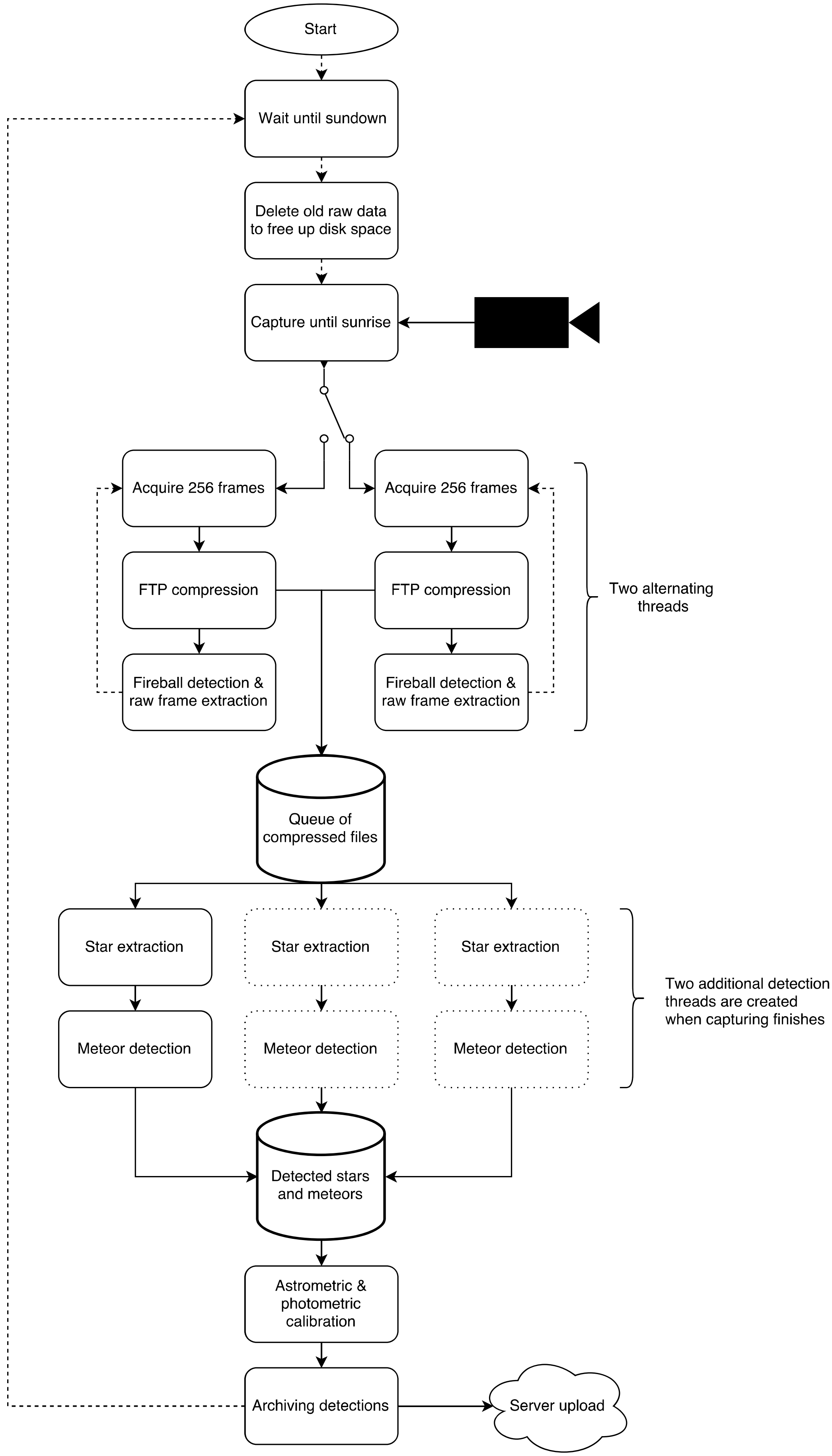

Figure 3 – Updated data processing pipeline.

where $\bar{d}$ is the average residual between predicted and observed positions of stars (in pixels), while $N_{matched}$ is the number of matched stars. The matching between catalog and image stars is done iteratively, starting with a star matching radius of 10 pixels. Next, it is reduced to 3, 1.5, and finally to 0.5 pixels. Image stars which are within this radius will be matched to catalog stars – the largest radius is most useful when the camera has been slightly shifted, so the automatic recalibration will succeed in those cases as well. After minimization with a certain matching radius is performed, this radius is decreased and a smaller number of false matches should be present in every subsequent iteration. Similarly to Šegon (2009), we use a subset of several thousands of stars detected throughout the night for astrometric calibration, which makes the fit more robust.

Finally, image centroids of detected meteors are converted to celestial coordinates with the refined astrometric solution, the photometry is performed, and the detections are archived and uploaded to the central server.

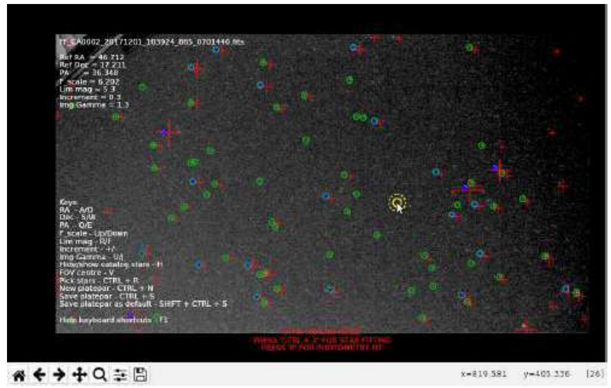

Figure 4 – SkyFit during star matching. Red crosses are catalog stars and their size reflects the magnitude, blue Xs are matched image stars and green circles are stars that were automatically detected on the image with our star extraction algorithm. The yellow circle is mouse cursor position (concentric circles are the annulus for centroiding whose size can be changed).

4 Creating an initial astrometric plate

The astrometry calibration process described above requires an initial astrometric plate which can be created with SkyFit, a program that is a part of our software package. The procedure begins by loading FTP compressed images into SkyFit and the user is prompted to enter an approximate altitude and azimuth of the centre of the FOV of the camera. The catalog stars are then projected on the image and the user can manually adjust the basic astrometric parameters (right ascension and declination of the FOV centre, scale, and image rotation). When the catalog stars are near the image stars, the user can manually pick and match image stars to catalog stars. At least 14 stars are needed for a robust fit. Figure 4 shows a screen shot of SkyFit during manual star picking and matching. Once enough stars are picked, the plate fit procedure is performed. Photometry fit can be viewed in a separate window.

In the future, we plan to host a public service on our server for automatic estimation of astrometric parameters which will be based on `astrometry.net` (Lang et al., 2010). This service will make SkyFit obsolete, but until then, it will be the preferred way of creating astrometric plates.

5 Orbit estimation results

In August 2017, during the Višnjan School of Astronomy (VSA) in Croatia, first multi-station tests with two temporary stations were conducted. One station was located in Višnjan and one in Pula, with 45 km between them. The Višnjan station consisted of four Sony Effio 673 cameras, two with 4 mm and two with 16 mm lenses, while the station in Pula consisted of one camera with a 6 mm lens. During several days of data collection, only a few common meteors between these stations were recorded, mainly due to poor volume overlap and unreliability of the code at the time. The first common meteor was captured on August 19 at $00^{\mathrm{h}}10^{\mathrm{m}}46^{\mathrm{s}}$ UT above the Adriatic sea. Using the methods of Ceplecha (1987) and Borovicka (1990) we have estimated the trajectory and the orbit of the meteor, while the uncertainties of every parameter were estimated by adding Gaussian noise equivalent to the measurement error (see Figure 5, the measurement error was about 0.5 arc minute) to the data and running 50 Monte Carlo iterations. The same meteor was independently captured by four stations of the Croatian Meteor Network (CMN) and its orbit was estimated using UFOOrbit[e] software. Table 1 shows the comparison of the two orbit solutions. The orbits are very similar, most parameters were within one standard deviation from each other. We consider this independent confirmation as a proof of quality of data produced by our software, especially when considering that the convergence angle (Q_C in Table 1) of our solution was only about 15°, while the CMN solution had a significantly better geometry. The orbital solution indicates that the meteor was a sporadic from the apex source.

[e] UFOOrbit software, `http://sonotaco.com/soft/e_index.html`, Accessed December 31, 2017

Table 1 – Comparison of orbital elements of a meteor recorded on 2017 August 19 at $00^{\mathrm{h}}10^{\mathrm{m}}46^{\mathrm{s}}$ UT. In the CMN column are the orbital parameters obtained using Croatian Meteor Network data and UFOOrbit, while the RMS column lists orbital parameters estimated with our software.

	CMN	RMS
Q_c	74.52°	15.99°
RA_G	48.679°	$48.436 \pm 0.244°$
Dec_G	+8.757°	$+8.656 \pm 0.029°$
V_G	$66.920\ \mathrm{km\,s^{-1}}$	$66.780 \pm 0.305\ \mathrm{km\,s^{-1}}$
a	3.379 AU	3.265 ± 0.218 AU
e	0.719	0.712 ± 0.027
i	163.930°	$163.806 \pm 0.157°$
ω	31.533°	$33.683 \pm 0.156°$
Ω	325.983°	$326.300 \pm 0.0002°$

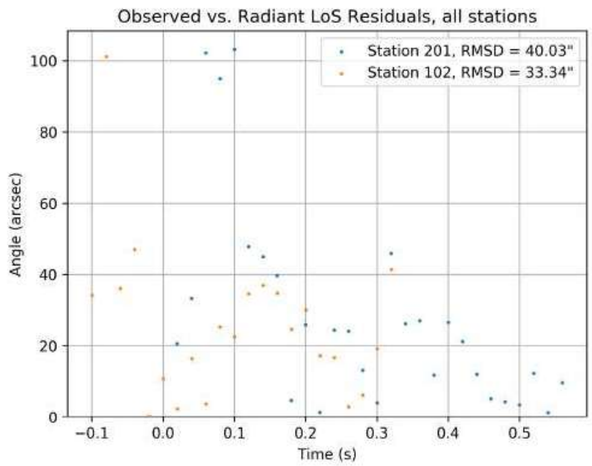

Figure 5 – Trajectory angular residuals of the 2017 August 19, $00^h10^m46^s$ UT meteor, observations with Raspberry Pi systems. The standard deviation of observations from the fit was about half an arc minute. Pixel scale for station 102 (Višnjan) was $5.3\,'\,\mathrm{px}^{-1}$, while for station 201 (Pula) it was $3.5\,'\,\mathrm{px}^{-1}$.

6 Feasibility of CMOS IP cameras for meteor work

In 2015 Sony announced[f] that they will discontinue manufacturing all CCD sensors in March 2017 and completely focus on CMOS sensors. This news will have a significant impact on meteor video observations, as practically all major networks are using cameras with Sony CCD chips (Jenniskens et al., 2011; Brown et al., 2010; Tóth et al., 2015). Furthermore, it is to be expected that the lower price range, explored by Samuels et al. (2014), will be most affected as it will take time for the new technology to come down in price. So far, a viable low-cost alternative has not been explored for meteor purposes and several concerns remain – mainly about the sensitivity and linearity of CMOS sensors, which may affect the quality of meteor photometry. Furthermore, many CMOS sensors at the lower price range (below $100 USD) have a rolling shutter, while global shutter cameras are only found in the upper price range. In rolling shutter cameras each row of pixels starts its integration in a staggered fashion from top to bottom over the frame time, thus each row represents a different time start/slice relative to its neighbors. On the other hand, in global shutter cameras all pixels start and stop their integration simultaneously. Here we explore one low-cost CMOS sensor, the Sony IMX225, and discuss its feasibility for video meteor work.

We have tested a digital IP camera with the IMX225[g] sensor and the HI3518E DSP. The camera has a resolution of 1280×720, compresses the video stream with the H.264 compression and is capable of frame rates up to 25 frames per second. An analog HD version of the camera is available as well. We have found that Raspberry Pi 3 supports hardware decoding of H.264 video, which adds near-zero overhead to the processing time, despite the total number of pixels being more than two times larger compared to lower resolution video from EasyCap devices (720×576). The sensor is 12-bit, but the images are downsampled to 8 bits during the H.264 compression.

Figure 6 – A meteor captured with the IMX225 CMOS camera. Visible constellations are Gemini (centre) and Auriga (right). The image is a 10.24 s maxpixel obtained using the Four-frame temporal pixel compression method.

Hankey and Perlerin (2018) tested the IMX290[h] camera, while IMX174[i] is being tested by Pete Gural (private communication). By looking at their stated specifications, the IMX225 is the most sensitive of all, having a sensitivity of 2350 mV at 1/30 s exposure, compared to 1300 mV for IMX290 and 825 mV for IMX174, although the IMX174 has a larger sensor and pixel pitch size. Furthermore, other advantages of the IMX225 is that the sensor is progressive scan (no interleave) and the IP board versions of the camera can be bought for as little as $20 USD, which make it a good candidate for testing. We have equipped the camera with a 4 mm lens ($64^\circ \times 36^\circ$ FOV, $\sim 3\,'\,\mathrm{px}^{-1}$ scale) and found that the camera is more than sensitive enough for video meteor purposes, with the gain set to 50% more than half the detected meteors were saturating, while the stellar limiting magnitude was about $+5.5^M$ from London, Ontario (Canada), which is under heavily light polluted skies. In the end, we have settled on 20% gain which gave a stellar limiting magnitude of about $+5.3^M$, with no major loss in the number of detected meteors, but with improved dynamic range. Figure 6 shows an example of one captured meteor with the setup.

Next, we explored the quality of photometry as there are concerns about linearity of CMOS sensors. We used stars from the SKY2000v5 catalog (Myers et al., 2015) for photometric calibration, which lists Johnson-Cousins magnitudes in U, B, V, R and I bands (Johnson & Morgan, 1953; Cousins, 1976). Not all stars have entries for R and I bands, thus we have derived them from

[f] IMPERIX response to Sony's CCD manufacture discontinuation, `https://www.imperx.com/latest-news/sony-discontinues-ccd-image-sensors/`, (Accessed December 31, 2017)

[g] IMX225 Sony website, `http://www.sony-semicon.co.jp/products_en/new_pro/october_2014/imx224_225_e.html` (Accessed January 1, 2018)

[h] IMX290 Sony website, `http://www.sony-semicon.co.jp/products_en/new_pro/february_2015/imx290_291_e.html` (Accessed January 1, 2018)

[i] IMX174 Sony website, `http://www.sony-semicon.co.jp/products_en/new_pro/december_2013/imx174_e.html` (Accessed January 1, 2018)

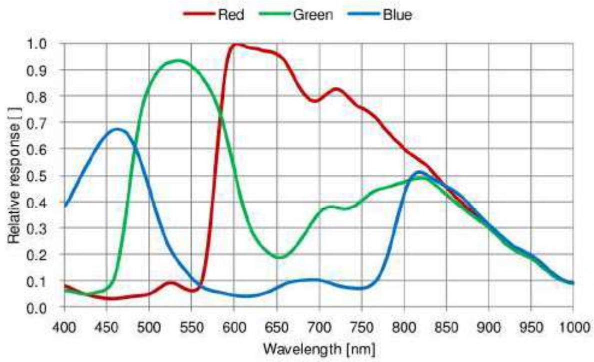

Figure 7 – IMX225 spectral response. The sensor uses a standard Bayer filter and during the conversion from color to B/W, the green channel is added in twice: $I_{BW} = R + 2G + B$. Source: IMX225 datasheet.

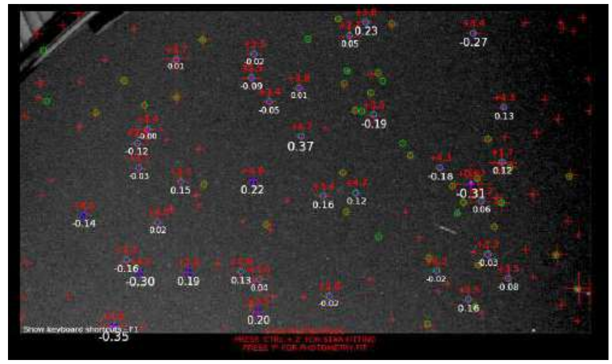

Figure 8 – Photometry done in SkyFit. Red numbers above stars are catalog magnitudes in our instrumental band, while white numbers below the stars are deviations in magnitude from the fit.

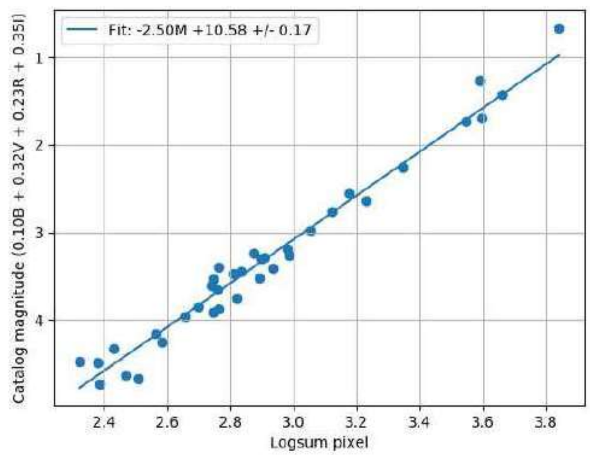

Figure 9 – Photometry fit on stars shown in Figure 8.

V and B magnitudes, following the method of Caldwell et al. (1993). After performing a fit on stars which had entries for magnitudes in all bands we arrived at the following relation for R magnitudes:

$$R = V - 0.77(B - V) - 0.04 \qquad (2)$$

We have estimated I magnitudes by following Natali et al. (1994):

$$I = B - 2.36(B - V) \qquad (3)$$

Following the method of Jenniskens et al. (2011), we have estimated the instrumental magnitude from the spectral response of the IMX225 sensor (Figure 7) as $0.10B + 0.32V + 0.23R + 0.35I$. Photometry was done without vignetting correction and with no flat field applied to the image. Figure 8 shows the stars chosen for photometry, while Figure 9 shows the photometric fit. The scatter at fainter magnitudes is due to the lower signal-to-noise ratio at those magnitudes, while at brighter magnitudes saturation effects appear. Nevertheless, the fit is linear between magnitude 0 and 5, while saturation correction will be needed for brighter meteors. We find that in the linear response region the quality of fit (1σ of $\pm 0.17^M$) is similar to the CAMS photometric fit given in Jenniskens et al. (2011), which used analog CCD cameras for data collection. The H.264 compression does not seem to have adverse effects on the photometry of stars, while comparison of meteor photometry from several stations will be done in the future.

Finally, the only concern that remains is the influence of the rolling shutter on the centroids of meteors as they move across the image plane. Early results of simulations are showing that it is negligible for slow meteors and meteors moving near-horizontally across the image plane, which means that the effect should be minimal for all-sky FOVs but may be of concern for moderate to narrow FOVs. This will be thoroughly explored in a future paper and a correction for the effect will be given.

7 Conclusion

We have presented an updated pipeline of the RMS software, demonstrated sufficient quality of astrometry and verified the implementation by comparing an orbit obtained using our software with Croatian Meteor Network observations of the same meteor. The orbit matches well and is within one standard deviation of the orbit independently estimated with UFOOrbit.

We have found a possible CMOS replacement for low-light CCD sensors that are in use before but are no longer manufactured. The IMX225 camera was shown to be sensitive enough for meteor work (stellar limiting magnitude of $+5.3^M$ with a 4 mm $f/1.2$ lens from a heavily light polluted location), and the camera response is linear for a range of 5 magnitudes. The only remaining concern is the influence of the rolling shutter on meteor centroids, but the correction method is being developed and will be published soon. The short-term plan is to set up a permanent multi-station configuration for trajectory estimation testing, and to grow the network globally in the long term. Interested individuals are encouraged to contact the authors for more information as meteor station kits running our software will be available on the market in the near future.

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9 Author Contributions

DV wrote the paper and most of the RMS code. MJM worked on hardware development, installation and testing. DŠ procured the hardware used at VSA2017 and provided many useful suggestions. DZ helped solve obstacles in the code which seemed insurmountable at the time. PK, FP and AM participated in VSA2017 where they helped to build hardware, install systems, collect and analyze data.

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