Estimating the IP from observations of bright extended polarised objects

Previous models of the Instrumental Polarisation (IP) have been derived from multiple observations of a bright unpolarised point source (Uranus). However, the measurement of the IP produced by Uranus at 450 um is difficult because of the high noise at 450 and the low level of IP. The current model (known as "JAN2018" - see IP model without the wind blind) has been shown to be inaccurate. For instance, Q and U maps of DR21 at 450 um show significant variation in brightness and morphology as the azimuth and elevation of the observation changes (see my report attached to the minutes of the 20190219 BISTRO DR telecon, available on the BISTRO wiki).

This report describes an alternative approach to estimating the IP model. Instead of using observations of Uranus, it uses observations of any bright extended source (any intrinsic polarisation in the source is ignored). It has been applied to observations of OMC1 (Orion A), DR21 and G34. The IP model derived in this way is consistent with the existing IP model at 850 um, but is significantly different at 450 um.

Overview

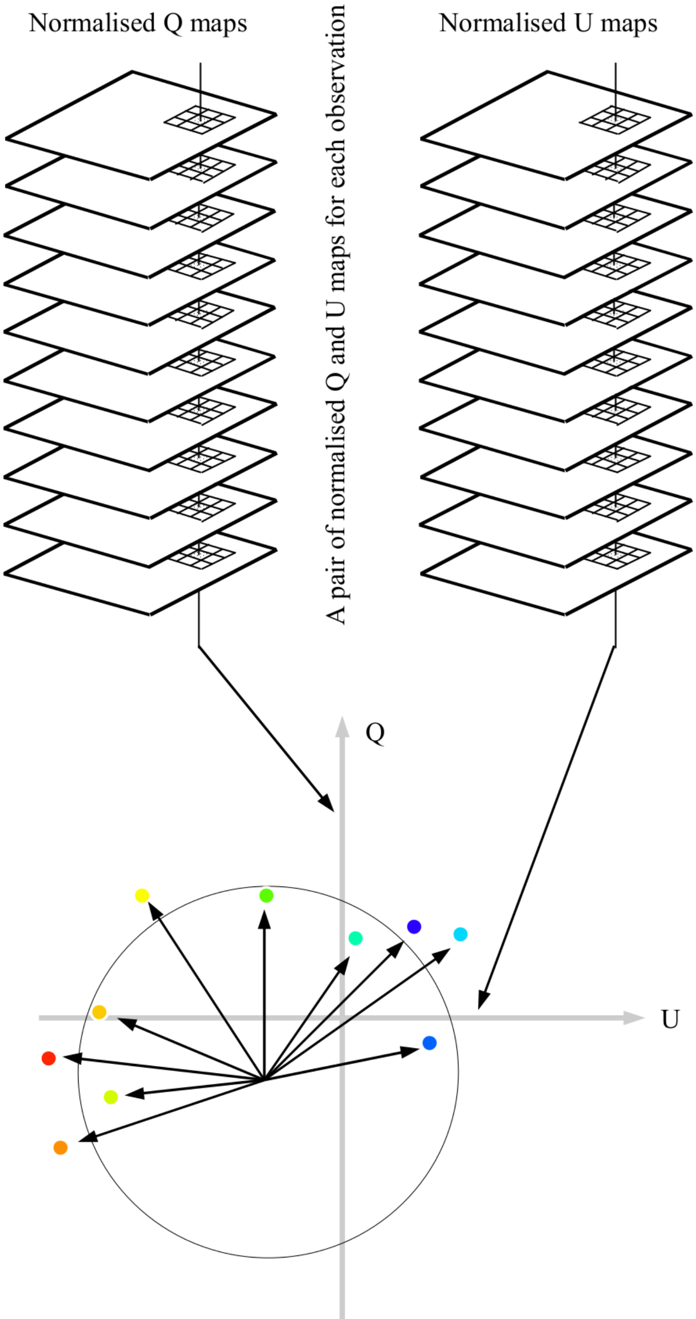
The new approach is based on analysing I, Q and U maps made from a set of 9 or more observations of a single object (450 and 850 data are analysed separately). The object must be sufficiently bright to allow good measurements of Q and U to be made from each single observation, without needing to co-add them. The models derived from each such object can then be combined to create a final master IP model.

For a single object, separate I, Q and U maps are created from each observation. This is done using `pol2map`. Initially (step 1), `pol2map` is used to create an auto-masked I map from each observation, which are then co-added. At step 2, `pol2map` is run again to create I, Q and U maps from each observation, using the co-add created at step 1 to define an external mask. Note:

1. No IP correction is performed when creating the Q and U maps, so the effects of IP are still present in the resulting maps.
2. The Q and U values created by `pol2map` use tracking north (usually Declination) as the polarimetric reference direction.
3. `SKYLOOP` cannot be used here as each skyloop iteration merges the IP from all observations, making it impossible to extract the (az,el) dependency.

Next, the Q and U maps for each observation are normalised by dividing them by the I map for the same observation. This removes any variation between observations caused by changes in the FCF, since such changes will affect I, Q and U equally.

Each source pixel (i.e. each pixel within the AST mask) is then considered in turn. At each pixel each observation provides a single normalised (Q,U) point, and the (Q,U) points for all observations can be plotted as a scatter plot as shown below:

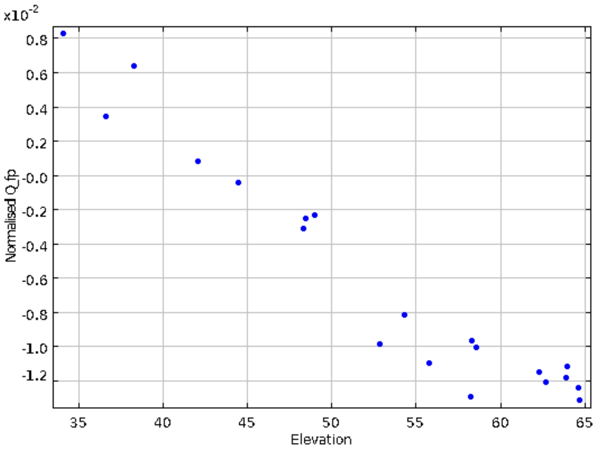


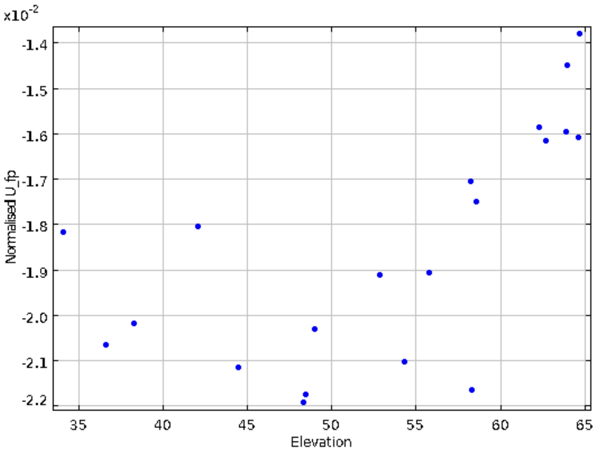
The points in such a scatter plot are scattered around an arc of a centro-symmetric shape (roughly a circle), with the true (Q,U) at the centre. The displacement of each (Q,U) point from the centre is a measure of the IP present in a single observation at the position of the pixel being used. Each observation is taken with the object at a different azimuth and elevation, resulting in the IP pushing the point away from the true (Q,U) along a different angle (in fact each observation covers a small range in elevation and azimuth). Due to sky rotation, there is a strong tendency for azimuth to vary monotonically in a clockwise direction around the circle, as shown by the variation in colour from red to blue in the above diagram.

The normalised (Q,U) offsets (i.e. offsets from the fitted centre) found above are with respect to tracking north, and next need to be rotated so that they are with respect to the focal plane Y axis.

$$Q_{fp} = Q_{tr}*\cos(2*\alpha) + U_{tr}*\sin(2*\alpha)$$
$$U_{fp} = -Q_{tr}*\sin(2*\alpha) + U_{tr}*\cos(2*\alpha)$$

where "α" is the angle from tracking north to the focal plane Y axis, in sense of North through East, at the central epoch of the observation. The "tr" subscript indicates (Q,U) with respect to tracking north, and the "fp" subscript indicates (Q,U) with respect to focal plane Y axis. The resulting Q_{fp} and U_{fp} values can be plotted as functions of elevation. For instance, the following plots show Q_{fp} (left) and U_{fp}(right) values for a single bright pixel in the 20 available observations of OMC1 (Orion A):





The above circle-fitting and rotation process is applied to every pixel within the AST mask, resulting in many more points being included in the above two plots. The numerical parameters (A,B,C,D) of the IP model are then found by doing a least squares fit to all the points in these two plots. The fitted IP model uses the same mathematical form as that used by the existing Uranus-based IP model:

p = A + B*el + C*el*el
Qfit = p*cos(-2*(el - D))
Ufit = p*sin(-2*(el - D))

where "p" is the fractional polarisation caused by IP at elevation "el" radians and (Qfit,Ufit) are the predicted normalised Q and U offsets with respect to the focal plane Y axis. The parameters A, B, C and D are chosen to minimise the weighted mean of the squared residuals:

$$\text{sum}(w*((Qfit - Q_{fp})^2 + (Ufit - U_{fp})^2))/\text{sum}(w)$$

where "w" is the weight associated with each (Q_{fp},U_{fp}) point.

What if the real shape is not circular?

The actual shape formed by the (Q,U) values in tracking coordinates will be circular only if the fractional polarisation due to IP (i.e. "the radius") is constant- i.e. if constants B and C in the IP model are both zero. In fact there is some evidence that the fractional polarisation varies slightly with elevation. This means that the actual shape may deviate slightly from a true circle. However, symmetry demands that the shape be centro-symmetric and so fitting a circle should give an accurate centre position even if the actual shape is not circular. It should be noted that the procedure described above uses only the fitted centre and does not depend on the fitted radius. It should thus be accurate even if the fractional polarisation is not constant.

Weighting and data cleaning

In general, relatively few pixels have sufficiently bright Q and U to form a well defined circular fit in the (Q,U) plane. To make the most of the data available, the N_{obs} (Q,U) points at each pixel (where N_{obs} is the number of available observations) are first binned into roughly 5 bins according to their azimuth values (badly aberrant points are excluded from these bins) - the circle is then fitted to the mean (Q,U) in these bins. After each fit, the RMS of the residuals of the original N_{obs} points from the fitted circle is found. If the largest residual is more than 3 times the RMS residual, the (Q,U) point with the largest residual is rejected and a new fit is performed.

Circular fits are rejected entirely if any of the following conditions are met:

1. the final RMS residual ("RMS" below) is larger than half the radius (the circle fitting procedure includes debiasing for the tendency to over-estimate the radius of very noisy circles).
2. the angle subtended at the circle centre by all the usable (Q,U) points is less than 120 degrees
3. the coefficient of correlation between the azimuth of each (Q,U) point and its position around the circle ("cor" below) is less than 0.7

Each circle is then given a weight equal to:

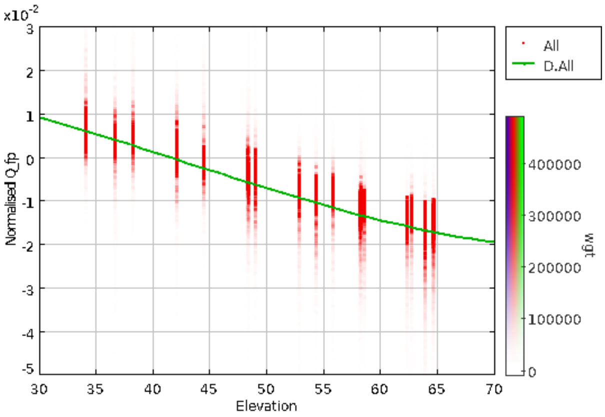
$$wgt_{circle} = (cor/RMS)^2$$

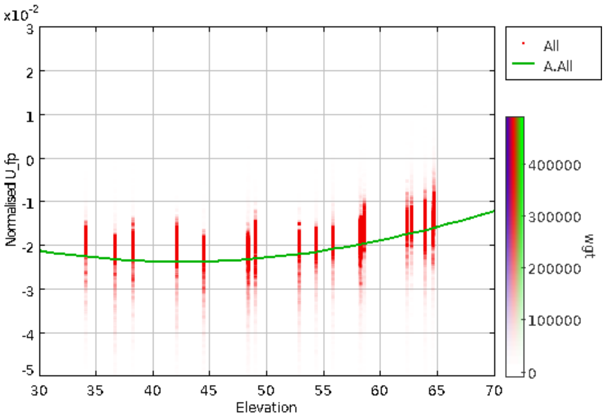
Thus to get a high weight, a circle must have low residuals and a high correlation between azimuth and the angular position of each point around the circle. The weight for each individual (Q,U) point ("w" above) is then the product of wgt_{circle} and a factor that depends on how far the azimuth of the point is from the best fitting line between azimuth and angle around the circle.

$$w = factor*wgt_{circle}$$

This factor is 1.0 for differences less than 20 degrees, and then drops linearly to zero at a difference of 60 degrees. The resulting weights are used when fitting the IP model to determine the values of the constants (A,B,C,D) above.

Below are shown the plots of Q_{fp} (left) and U_{fp} (right) against elevation for all usable pixels in OMC1/OrionA with the weight, "w", indicated by the transparency of the red dots. The best fitting model (Qfit,Ufit) is shown in green:





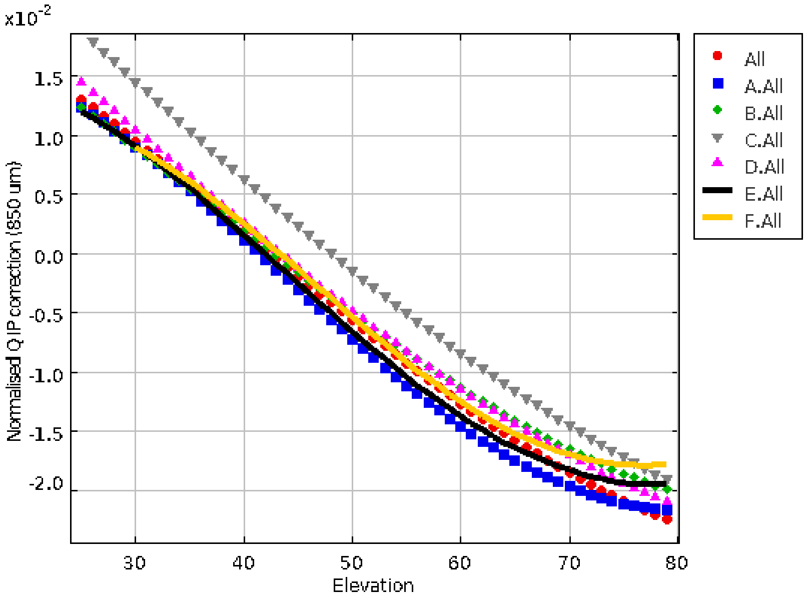
Comparing results from different objects

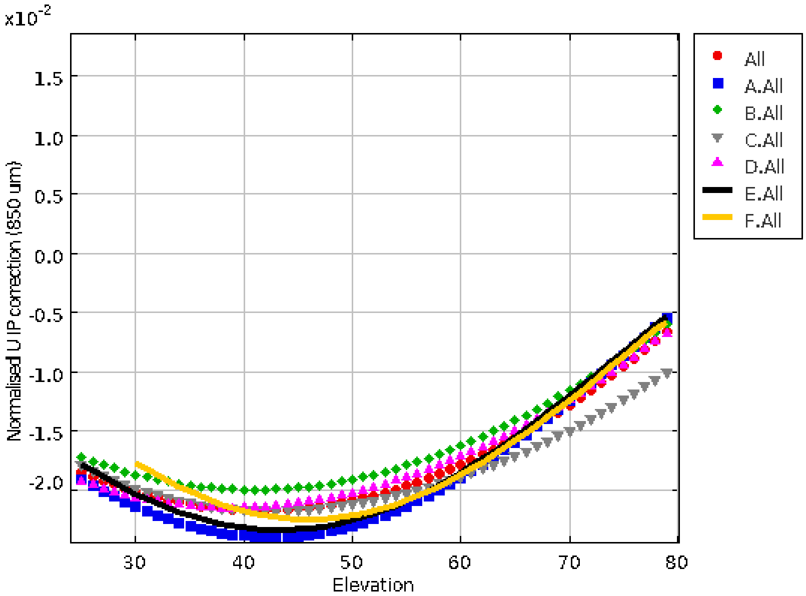
The above process was applied to the following observation sets:

1. 20 observations of OMC1/OrionA (blue markers in the plots below)
2. 12 observations of DR21 (red markers in the plots below)
3. 12 observations of G34 (pink markers in the plots below)
4. 20 observations of OrionB (green markers in the plots below)
5. 20 observations of Serpens main field 2 (grey markers in the plots below)

The new model fitted to the combined (Q,U) data from all observations is shown as a black line. The previous Uranus-based model (JAN2018) is shown as a yellow/orange line.

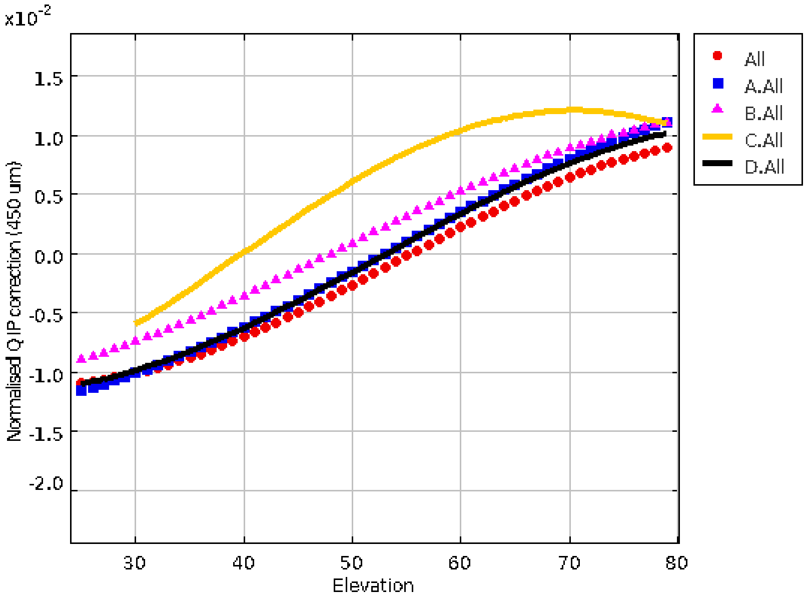
850 um results

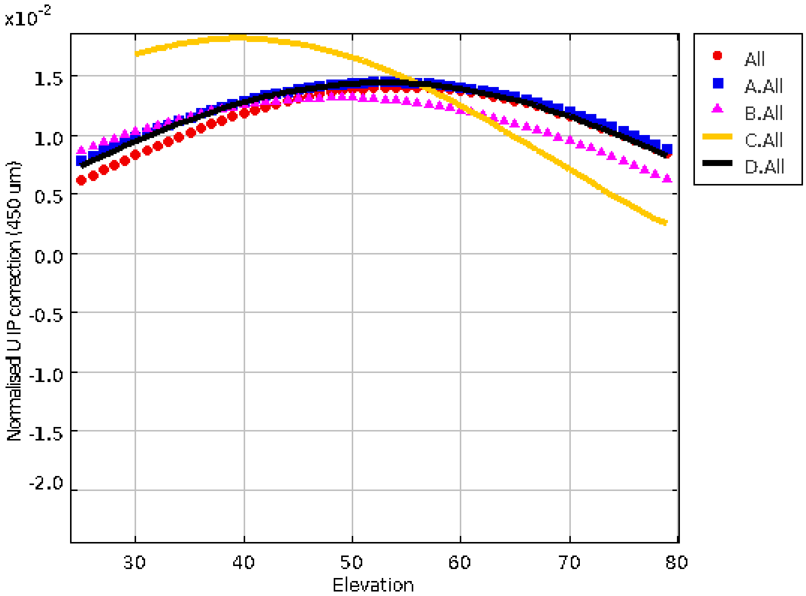




450 um results

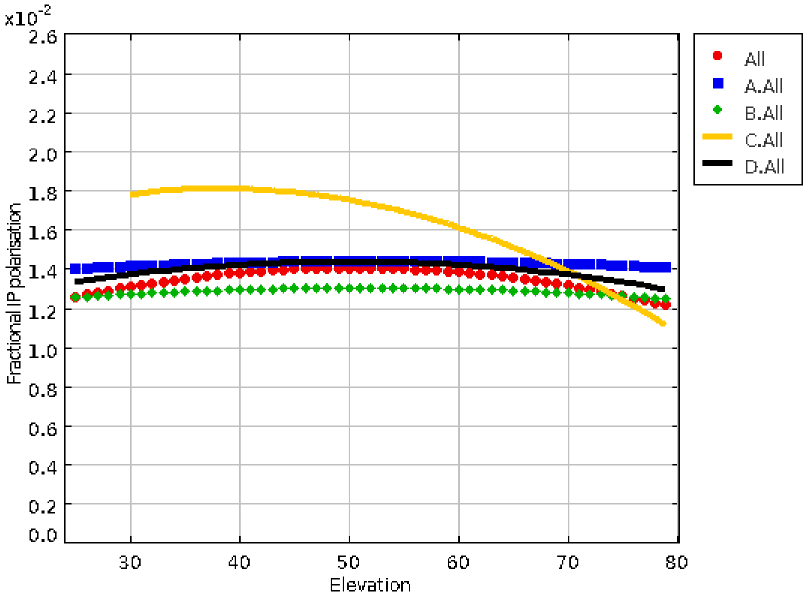
Note, neither OrionB nor Serpens provided any usable data at 450 um.

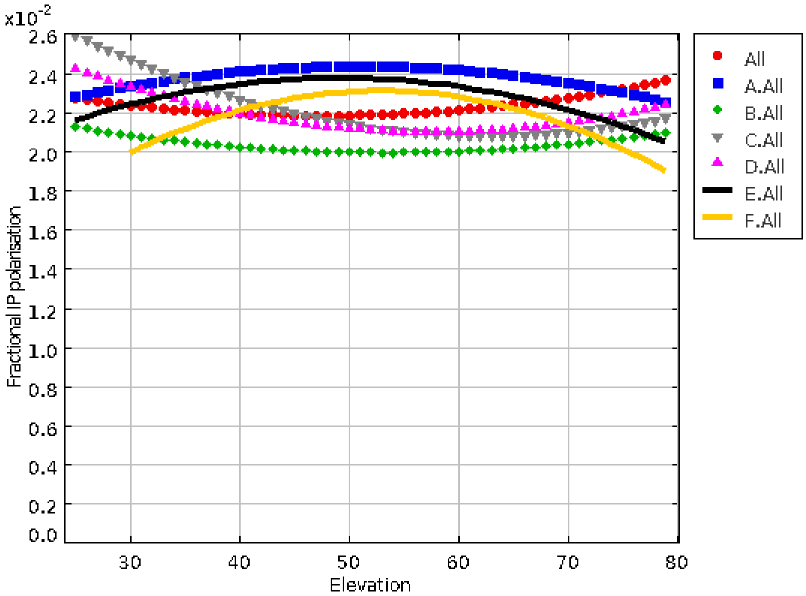




Fractional polarisation due to IP

The following plots show the fractional polarisation due to IP at 450 um (left) and 850 um (right).





Concluding remarks

A new command called `pol2ipcor` has been added to SMURF. This command takes a set of I,Q and U observations for a single field and creates a table holding the elevation, Q_{fp}, U_{fp} and weight for every usable point, using the proces described above. It can also take in a set of such tables created by earlier invocations of `pol2ipcor` and perform a fit to determine the values of the IP model parameters (A,B,C,D).

The new IP models at 450 um and 850 um have been installed into `makemap` and can be applied by adding "ipmodel=AUG2019" to the `makemap` config file. They have not yet been documented however, pending further testing.

Further testing should be done to check the effects of the new IP models on typical POL2 fields, and to see if the new 450 um model removes the variation with azimuth seen in DR21 (as described at the start of this article).