

# 1 Spherical Harmonics

The most popular, call it standard, definition of the spherical harmonics is

$$Y_\ell^m(\theta, \varphi) \triangleq N_\ell^m P_\ell^m(\cos \theta) e^{im\varphi}$$

where the normalization is given by

$$N_\ell^m \triangleq \sqrt{\frac{2\ell+1}{4\pi} \frac{(\ell-m)!}{(\ell+m)!}}$$

## 2 Numerical considerations

### 2.1 Normalization

As can be gleaned by looking at the asymptotics of the terms, computing  $N_\ell^m$  and  $P_\ell^m(z)$  *separately* causes numerical problems as  $\ell$  becomes large. Empirically, these problems emerge around  $\ell = 150$ .

Direct computation of *normalized or semi-normalized* associated Legendre functions, which essentially computes  $N_\ell^m P_\ell^m(z)$  holistically, is a better numerical strategy.

We use the Schmidt semi-normalized Legendre functions because they are implemented in MATLAB as `legendre(1,m,'sch')`. Empirically, if problems emerge then they are for  $\ell > 2000$ .

#### 2.1.1 Schmidt semi-normalized associated Legendre functions

As defined and implemented in MATLAB, the Schmidt semi-normalized (associated) Legendre functions are:

$$\begin{aligned} \text{SP}(N,M;X) &= \text{P}(N,X), \quad M = 0 \\ &= (-1)^M * \text{sqrt}(2*(N-M)!/(N+M)!) * \text{P}(N,M;X), \quad M > 0 \end{aligned}$$

that is,

$$SP_\ell^m(z) \triangleq \begin{cases} P_\ell^m(z) & m = 0 \\ (-1)^m \sqrt{\frac{2(\ell-m)!}{(\ell+m)!}} P_\ell^m(z) & m > 0 \quad (m \leq \ell) \end{cases}$$

(available in MATLAB as `legendre(1,m,'sch')`).

In summary, the normalized associated Legendre functions and not the standard associated Legendre functions should be used when computing the spherical harmonics.

### 2.2 Symmetry

For negative  $m$  we note

$$Y_\ell^{-m}(\theta, \varphi) = (-1)^m \overline{Y_\ell^m(\theta, \varphi)}$$

so we only need to compute positive orders  $m$ . That is, if we have computed  $Y_\ell^m(\theta, \varphi)$  for  $m > 0$  then we can simply determine  $Y_\ell^m(\theta, \varphi)$  for  $m < 0$ .

In summary, with a few sign flips we can get the negative order spherical harmonics from the positive ones.

### 2.3 More robust spherical harmonic computation

Define

$$S_\ell^m(z) \triangleq (-1)^m \sqrt{\frac{2(\ell-m)!}{(\ell+m)!}} P_\ell^m(z), \quad m \geq 0 \quad (m \leq \ell)$$

and so we have

$$S_\ell^m(z) = \begin{cases} 2 S_\ell^0(z) & m = 0 \\ S_\ell^m(z) & m > 0 \end{cases} \quad (1)$$

in terms of the Schmidt semi-normalized Legendre functions (available in MATLAB as `legendre(1,m,'sch')`). Further define

$$Q_\ell \triangleq \sqrt{\frac{2\ell+1}{8\pi}}$$

Then we have

$$Y_\ell^m(\theta, \varphi) = \begin{cases} (-1)^m Q_\ell S_\ell^m(\cos \theta) e^{im\varphi} & m \geq 0 \quad (0 \leq m \leq \ell) \\ (-1)^m \overline{Y_\ell^{-m}(\theta, \varphi)} & m < 0 \quad (-\ell \leq m < 0) \end{cases}$$

### 2.3.1 MATLAB implementation

The Schmidt semi-normalized Legendre functions are available in MATLAB so we only need to modify the  $m = 0$  case, (1). The following code computes  $Y_\ell^m(\theta, \varphi)$  for  $\ell \geq 0$  and  $m \in \{-\ell, \dots, \ell\}$  on a separable grid in  $\theta$  and  $\phi$ :

```
function [Ylm,theta,phi]=sphereHarm(l,m,tt,pp)
%sphereHarm spherical harmonic of degree l and order m
if isvector(tt) && isvector(pp) && abs(m)<=l && l>=0
    tt=tt(:)'; pp=pp(:)'; % ensure they are row vectors
    [theta,phi]=ndgrid(tt,pp);
    Sl=legendre(l,cos(tt),'sch');
    Sl(1,:)=Sl(1,:)*sqrt(2); % m=0 adjustment
    Ql=sqrt((2*l+1)/(8*pi));
    Slm=Sl(abs(m)+1,:); % pull out S_l^|m|
    Ylm=(-1)^m*Ql*kron(ones(size(pp)),Slm).*exp(1j*abs(m)*phi);
    if m<0
        Ylm=(-1)^m*conj(Ylm);
    end
else
    error('** invalid inputs or out-of-range')
end
end
```