Announcement
Here is a note of Paul's lecture Basics of Radio Interferometry. The outline is basically the same as the layout of the ppt where almost all the information comes from, though with sparsely information obtained from other source(grey, and not always reliable(a few cannot be found in any authentic publications — if wrong, then it is me)).

I am sorry to tell that due to the limitation of energy and time, pictures and formulas will not be presented in this report, please refer to the ppt.

Welcome any kinds of corrections.

A. Radio atmospheric Window — why radio astronomy is useful

The earth's atmosphere absorbs most rays and prevent them to be detected by the ground-based telescopes, but radio waves and visible lights meet almost transparent atmosphere(although the effects of ionosphere and troposphere exist).

Further more, the radio window consists wide range of frequencies, which means various emissions can be detected on earth.

B. Thermal and non thermal radiations — where the radiation come from

Radio sources can be categorized into two class — thermal or non-thermal.

Thermal radiation follows the black body radiation law. Their brightness directly leads to their temperature.

Non-thermal radiation consists of synchrotron emission, which is emitted by electrons accelerate or decelerate in magnetic field, and jumps of electrons from one energy level to another, such as Zeeman effect, Hyperfine structure(21 cm line).

C. Single Dish Antenna — Basics

Antenna dish has various shapes but their cross-section are mainly parabola-like in order to collect the far-field waves to the feeds.

The 'area' conception of an antenna means the effective receiving area, considering the block area by the feed and other structures to support it, as well as the possible absorption and diffuse reflections on the surface of dish.

The output of antenna is a function of frequency, time, position and polarization. The polarization is measured by individual dipoles in forms as X/Y or RCP/LCP, which corresponds to shape of the feed. But we always use Stokes parameters(I Q U V) to represent the polarization. The position is presented by the direction vector s which corresponds to a specific location on the celestial sphere.

D. Single Dish Antenna — Output

The output of antenna is the power it received from the source as a whole in a specific frequency channel dv, whose unit is Jansky and is transformed to the form as Voltage(a complex number).

The resolution of telescopes is limited by the diffraction, which is inversely proportional to the diameter of the dish.

E. Single Dish Antenna — Target and differences with the output

The ultimately aim of telescopes is to measure the brightness of the source, which is not simply same as the power received by various reason:

The beam response : telescopes have different response with different direction, which can be understand as the effect of finite aperture. According to the Reciprocity Principle, we can image a transmitter who has the same structure as antenna. The beam it emits will not be merely a circle, but with side lobes around. The side lobes changes around zero, which leads to negative power in the graph, if not dealt properly.

The frequency response : antennas have different sensitivity towards different frequencies, sometimes we can even add filters to block some unwanted signals.
The dipole sensitivity : For those without circular aperture but build up in dipole pairs, the sensitivity of dipoles replaces the beam response of aperture. Dipole also has different responses toward different directions.

Considering the above factors as a whole, the beam reception pattern of an antenna can be built. The power received by an antenna is a convolution of beam's reception pattern and our target, the brightness distribution of the source, integrated over the source's surface.

F. The relation between single dish antenna and antenna array

The vivid pictures on the ppt revealed the procedure of a single dish antenna changes step by step into an antenna array, with delay compensated manually by adding different phase to the signals received.
The splitting of a single antenna has advantages : The resolution of the antenna is significantly improved by lengthening the baseline, which is the (projected) separation between antennas. Further more, by changing the delays which can be viewed as changing the shape of the equivalent single dish, the additional focus provides the chance of observing multiple sources at the same time. There are more advantages such as the uncorrelated noise cancelation, which increases the signal-to-noise ratio by cross-correlation.

G. Basics of interferometry — Two antennas

The signals from two antennas are multiplied with each other in the multiplier and then average in the integrator, where their product is firstly integrated with time and divided by the total length of time sequentially.
With the simplest example of two antennas' interference under the plane wave and the coplanar assumptions, the geometrical delay(and the instrumental delay) defines the final result, as the time averaging erases the time-varying component and only constant(geometrical delay) survives.

H. UV plane and Fourier transformation — multiple antennas

When the case antenna array is not coplanar, the projection of baseline have two components, u and v measured in wavelength, scrutinize the space coherence function of the integrator and find the Fourier transformation relationship between the visibility function on the projected baseline plane with 'ground' coordinates and the target plane(parallel to the other plane) which is the distribution of brightness measured in l and m as 'sky' coordinates. This Fourier transformation relationship is the essential of interferometry.

I. 'Issues' in invert transformation

If the Fourier transformation relationship is exact, it will be much easier for us to obtain a 'real' picture of the brightness distribution. But the reality tells cruel story.

a. The beam pattern

Same as what we encountered in the single dish case, the visibility is the convolution of beam pattern with the brightness function. Here needs additional information for the deconvolution process since the analytical solution of deconvolution cannot be obtained.
Based on the reality, scientists make some assumptions : The radio sky is composed of a certain number of(not infinite, for the convergence of CLEAN) point sources whose radiation is gaussian and any sources(especially those extend) is equivalent to some combination of point sources. For the convenience of calculation, a further assumption can be made : the point source is within some finite area, which is predicted by theory.

Here leads to the CLEAN algorithm, which consists major cycles and minor cycles. CLEAN finds the highest peak of the intensity and subtracts a response to a point source from the existing graph by a certain fraction, records the position and amplitude of the removed part, performing iteratively and leading to a reasonable solution of the deconvolution — clean image. This is performed in the image domain, on the 'dirty' image which is the directly Fourier transforming result of the visibility function while there are another algorithm which is executed in the 'frequency' domain.

The finishing criteria for CLEAN algorithm varies. A certain number of iterating steps, comparison of the highest peak with the rms level of the residual image, computing the ratio of negative components subtracted…just like the weighing function, this serves the scientific goal.

It compensates for the incomplete of sampling points on the uv plane, and can be viewed as a method of interpolation. But in the case when faced with hugely extended sources as sun, the efficiency of the algorithm falls. Further more, when bright radio sources in the side lobes appear, the algorithm may not gives satisfying results. Thus to say, it is not a 'true' deconvolution, but a numerical method.

b.The discret Fourier transformation
While the formula represents the Fourier relationship in integral, the computer calculates only the discrete sum. In order to achieve this, the plane needs to be gridded into small squares. A single square can contain zero or more discrete points, which is the domain of visibility functions defined on discrete uv projection of baselines, consequently they contain different amount of information. Thus leads to the weighing function. There are serval ways of weighing, which is basically a trade off between signal-to-noise ratio and resolution, and can only be decided by the different scientific goals.

c.The missing of points
Our observation does not covers the entire surface of uv plane(which is not possible), so the incomplete invert Fourier transformed graph cannot reveal all the truth. But one thing is certain : the more points known on the UV plane, the better the quality of the picture. We can enhance uv coverage by serval means.
Earth rotation : as the antennas rotate with earth, the points will move and eventually form a line on the uv plane, which increase the coverage.
Combine with other antennas : In the 'frequency' domain or uv plane, we can add single dish observation results so as to compensate for the missing of (0,0) point. The combination does not confine to single-dish and antenna arrays, it can occur between arrays.

d.The non-coplanar of antennas
In the case where the electric field canon be treated as far field or plane light, for nearby sources as fireballs, moon and debris, a 3D Fourier transformation is needed. In the actual computing procedure, we add w components and performing sliced 3D — 2D Fourier transformation to individual slice of space, and finally select the points on our curved plane and combine them together. The algorithm for this is called w-projection, there are another faster algorithm designed specifically for MWA measurements called WSCLEAN.

J. Calibration
Calibration is a way to get rid of many undesired effects from all kinds of reasons. Fortunately, the effects mainly affect individual antennas rather than their combinations. This is to say, the effects on the outputs can be resolved into two components Ji and Jj responsible for each antenna, independent of each other and Jij which corresponds to the baseline seldom appears. Calibration uses theoretically prediction, data known to scientists and measured data from calibrator sources,

which is a resolved , bright source, always close to the observation centre, to solve the Ji and Jj. When polarizations are concerned, Ji and Jj are complex 2 by 2 matrixes.

The bandpass response, absolute magnitude and absolute location, ionospheric Faraday rotation and polarization leakage, needs the measurement of calibrators, while the geometric compensation, parallactic angle, tropospheric effects are those can be estimated and antenna voltage pattern, electric gain is already known.

K. Flagging

Flagging is to erase the frequency channels in a specific period when they are corrupted by the radio frequency interference(RFI), whose magnitude is enormous and uneasy to predict. RFI leads to the lose of information and increase of noise overall, it is usually the first step of information processing and always done automatically when downloads the measurements data from the Internet, since there are plenty of algorithms dealing with RFIs.