Society of Amateur Radio Astronomers (SARA)
PROTOCOL FOR THE MEASUREMENT OF
RADIO OCCULTATION EVENTS,
DATA, AND SYSTEMATIC MULTI-OBSERVATIONS

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Prepared for

Analytical Section
Society of Amateur Radio Astronomers

Acknowledgements

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Disclaimer: This protocol is intended as a guide for amateur radio astronomers and not for professional observational use. For professional use, the referenced documents are advised for the precision required in professional astronomical observations. Please direct communication on errors found and enhancement suggestions for this guide to the Analytical SARA Section Coordinator.

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Radio Occultation Protocol

Background

The Radio Occultation Protocol was written for SARA after interactions between members of IOTA and SARA revealed an interest in exploring the measurement of radio occultation events, databases, and systematic multi-observations. The protocol was developed to assist amateur astronomers quickly learn the basics of radio occultation methodologies without having to research numerous professional journal papers. Afterwards, an amateur could make a determination if the instrumentation available to him or her is sufficient in recording a radio occultation event.

Purpose

The purpose of this protocol is to assist the amateur radio astronomer in recording a radio occultation event by presenting a summary of considerations. This protocol presents background information and context so that the amateur can evaluate the challenges to be encountered with a radio occultation observation event. Depending on the ability and skills of the amateur, it is recognized that the main impetus is to record an event, and not necessarily define it to a high degree of accuracy. An analogy might be made to the amateur who delights in obtaining a low-resolution optical image in his or her first attempt at imaging, rather than attempting to obtain a high resolution print from the onset. The goals can vary in an observation of a radio occultation, but they usually are:

- Identify the optical/radio source to be occulted
- Obtain a brightness distribution
- Obtain position and structure profile

Lunar Occultation of Radio Sources

Lunar occultation of radio sources is the most common type of radio occultation observed. Lunar occultation events have been successfully used to measure stellar angular diameters. Radio astronomers in the 1960s began using the technique to measure the arc-second angular structure of radio sources. More importantly, the radio structure could be measured with radio telescopes that have tens of meters diameters and beams with angular sizes of tens of arc-minutes.

For a number of years the highest resolutions were obtained by observing the diffraction pattern of a radio source as it was occulted by the Moon. Most of the analysis was based on a technique described by Scheuer (1962) and later extended by von Hoerner (1964) to restore the true brightness distribution from the observed Fresnel diffraction pattern. The maximum resolution is generally limited by the sensitivity of the telescope.

Each occultation gives only a one-dimensional "strip" distribution. Several occultations are required to reconstruct the two-dimensional structure. At the shorter wavelengths, the Moon is an intense source of thermal radio emission and the small tracking irregularities present in radio telescopes may completely mask the occultation of the much weaker extra-galactic sources. Interference from terrestrial radio emission reflected from the Moon is often a serious problem.

Procedure

There are several procedures for radio occultation events depending on whether the Moon, a comet, or a planetary body is involved. Furthermore, procedures differ for single antenna and interferometry. Rather than detail individual procedures, this protocol highlights the actions that should be considered. Depending on choices made, detailed journal papers can be consulted.

Scheuer (1965, MNRAS, 129, 199) described a method for radio occultations (which is available on internet). Scheuer defines a restoring function that is the second derivative of the Fresnel diffraction pattern convolved with a Gaussian. The restoring function is convolved with the observed data to produce the radio source structure. Rather than fret on details developed by Scheuer to minimize error and refine resolution, a good starting point is perhaps to observe and record data, having attempted as much sophistication as possible in the planning stage. Depending on one's skill, a variety of considerations can be attempted for improving the accuracy of the observation:

- Scheuer Procedure: Scheuer developed a method removing effects of Fresnel diffraction at limb of Moon (i.e., the Moon is a diffracting screen)
- Lunar Occultation Method (Swarup et al 1971)
- Optimum Deconvolution Method (ODM)

Furthermore, various considerations can be given to errors and assumptions involved in a lunar radio occultation observation:

- The Moon's limb is small and the occultation curves may be considered as diffraction curves of straight edge
- The effect of local irregularities of moon's limb can be neglected
- The Interferometric method eliminates background effects
- A correction of 0.4 arc sec can allow for known irregularities on the Moon's limb
- Errors can occur in positions and diameter measurement
- Single telescope observation of the lunar occultations are prone to changes in receiver power output due to imperfect telescope tracking of the presence of the moon which radiates blackbody temperature at about 230K
- The background temperature increases at low frequencies and is helps to reduce the effects of poor tracking in the region of the Moon
- At high frequency when the telescope beam is smaller than diameter of the Moon and hot Moon is in the side of the beam: Under these conditions small errors in tracking can lead to large fluctuations in receiver output. These problems can be overcome by use of interferometer, which resolves the Moon strongly.
- Effects of interference on the output of the receiver can be reduced
- Errors can occur in discrepancy between occulted flux density and total flux density

- Errors can occur with another discrete source strong enough to confuse observations
- At millimeter wavelengths the contribution from the Moon can be as high as the receiver noise temperature
- In a strong galactic emission region, and when the Moon is in the center of the aerial beam, the effect due to the obscuration of the background is comparable to that due to the occultation of the source
- RMS value of the noise
- High resolution only with large signal to noise ratio
- Because the Moon is moving through the sky at a different rate, the frequency of any lunar fringes will differ from that of the source
- Interferometer output due to the Moon can be 0 to 2 flux units, but at low projected baselines this can rise to 10 flux units
- Dimensions of interferometer will tend to smooth the diffraction pattern on the surface of the Earth: point source will appear to have finite diameter
- Use of interferometer provides greater sensitivity and overcomes problems of interference and telescope tracking imperfections, but the analysis requires considerable attention
- Fringes from the Moon and from confusing sources with the telescope beam exist, both of which can be same order of amplitude as the occulted sources
- Irregular nature of Moon's limb is main source of error in deriving brightness distributions
- Interference, instabilities, excessive baseline drafts
- Change in phase of observed fringes: A better procedure is to deduce the phase of the source vector from the observed vector just before and after occultation and consider only that component of the observed vector having this phase
- System noise temperature including contributions from the Moon, sky, and ground reflections
- Position of center of Moon can be found by taking hourly geometric coordinate from nautical almanac interpolating half-hourly values, and correcting these for parallax with the formula given by SMART
- Distribution of the degree of polarization along the limb is not uniform

Determining Occultation Events

Predictions of lunar occultation events of radio sources are made using the software called Lunar Occultation Workbench (LOW). Radio Sources with 1420 MHz and 4.8 GHz fluxes greater than 1 Jy are included in LOW. The LOW software provides an excellent summary of all aspects of an occultation. Other sources include published tables from Almanacs and Annual Handbooks.

Results and Comparison

Since the purpose of this protocol includes establishing a future database of standardized reporting, suggested data tables are provided for use and evaluation under Recording of Data. Moreover, graphical representations of radio occultation results are provided in all of the astronomical journal papers. These representations are numerous and expected when conveying results. Provided below is a comparison of the strip brightness distributions across Ooty survey radio source name OTL 0220+172 (a.k.a. 4C +17.12) derived using the ODM and Scheuer's method. This is one example of the types of figures desired in a professional analysis, and is taken from the reference in this protocol: Mem. Astr. Soc. India, 1, 25-47, 1979, Occultation Observations of 122 Radio Sources at 327 MHz: List 8, K.L. Venkatakrishna and G. Swarup. To obtain more information on the types of figures and tables for the presentation of results, review the references noted.

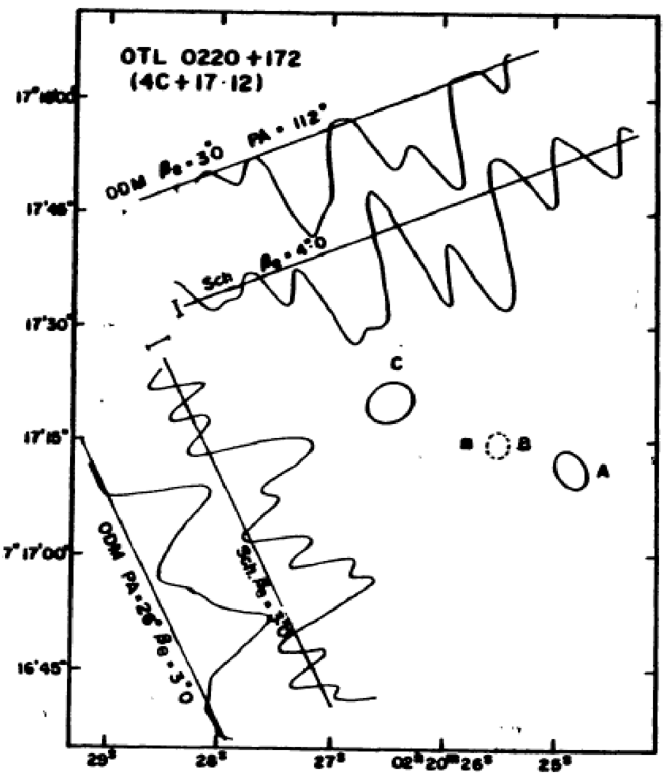


Fig. 1: A comparison of the strip brightness distributions across Ooty survey radio source name OTL 0220+172 (a.k.a. 4C +17.12) derived using the ODM and Scheuer's method.

Types of diagrams presented in the references include:

- Radio/Strip brightness distributions
- Strip scans
- Brightness profiles
- Schematic models of the structure
- Polarization distributions
- Vectorial plots, linear polarization
- Radio and optical occultation curves compared, with positions noted
- (Corrected) Occultation curves
- Occultation curves as percentage of unocculted source
- Centroids of radio emission
- Geometry of occultations
- Spectral image distributions

- Two, three, and four strip integrated brightness distributions and models of the radio sources constructed from them
- Space-frequency spectra or modulation index curves
- Spectra of radio source
- Solid curve spectra of whole sources
- Effective temperature of radio source, Brightness temperature
- Position angle of the strip integral of the brightness distribution

Discussion and Conclusions

The discussion and conclusion of amateur observations is going to vary greatly depending of the level of sophistication of the observation method, the radio source being occulted, the errors tolerated, and goals of the observations. Considerations for a discussion and conclusion section are noted below.

- The shape of the Fresnel diffraction curve
- Frequency dependence of the intensity distribution
- Strip brightness symmetry
- Data identification of radio jets with optical ones
- Radio spectrum flatness and steepness
- Variation of the optical to radio spectral index
- Apparent displacement of optical source from the major axis of the radio source
- Ratio of radio to optical brightness distributions and its variability

Group and Comparative Networking

A decision may be made to observe an occultation in both radio and optical frequencies, and compare results. The methods of amateur optical observation are well documented and by the International Occultation Timing Association (IOTA), which has a detailed Observer's Manual. The International Occultation Timing Association is the primary scientific organization that predicts, observes and analyses lunar and asteroid occultations and solar eclipses. IOTA astronomers have organized teams of observers worldwide to travel to observe grazing occultations of stars by the Moon, eclipses of stars by asteroids and solar eclipses since 1962

The Lunar Occultation Program at PARI takes advantage of the ability of multiple simultaneous frequency measurements, probing the arc-second structure of radio sources at those frequencies.

Recording of Data

Recorded data in professional journals vary in format but often contain the following standard elements.

Table 1. Sample Format for Data

Source Name, observation frequency, and Observing times UT	Flux & Flux density, S	R.A. and Declination (epoch 2000)	Position Angles, Position angle of axis of source, Position angle of major axis	Angular size, Apparent radius	Optical object, Optical objects in region	Source structure: Complex, Double, Single	Notes

Table 2. Sample Format for Radio Telescope Specifications

Telescope, Antenna, & Procedure Type	Location, Geometric area of radio telescope	Calibration Source and Minimum Resolution (at specified wavelength)	Type of receiver, Receiver power	Telescope field of view	Antenna tracking & Phase tracking programs	High frequency cables having low losses

Include the following information for the radio telescope if applicable:

- Contact Information
- Array Information
- Array Configurations
- Antennas
- Receivers
- Intermediate Frequency (IF)
- Correlator
- Sensitivity of the telescope (uniform or non-uniform)

Other Recorded Data Considerations include:

- Integration time during immersion
- Filters, MHz used (band-pass filters useful to limit noise)
- Variation in the intensity
- Modulation depth for the radio brightness distribution
- Polarization intensity
- Linear polarization measurements

- Background noise level, Noise figure
- Geometric of occultation
- Position of lunar limb
- Perform restoring function convolution
- Diffraction patterns can contain structures less than or equal to 2 seconds of an arc. Without fringes – angular diameter is at greater than or equal to 5”.

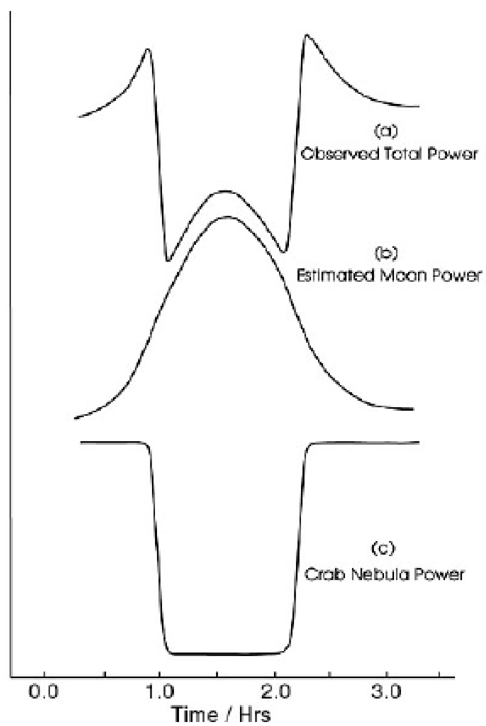
Other Instrumentation Considerations (if applicable) include:

- Aerial beam, Narrow beam antenna, Antenna beam
- Number of beams of the telescope and relative gains
- Crystal mixer input stages
- Unswitched double sideband receivers
- Electric axes, plane close to meridian
- Co-phased half-wave dipoles
- Criss-cross curtain antenna array
- System temperature (temperature sensitivity of observation)
- Receiver and necessary gain stability
- Gradient in received power
- Baseline orientation of interferometer
- Remote frequency amplifiers
- Number of radiometers operated simultaneously
- Beam width
- Primary beam attenuation
- Baselines
- Synthesis beam
- Phase switched interferometer
- Correlation type radiometers to reduce noise
- Fluctuation sensitivity
- Sidebands
- Interferometer lobe separation

Simple Signal Observations (for Beginner Amateurs)

The Crab Nebula is one of the strongest radio sources in the sky. The Moon is also a source of radio waves, as a warm thermal source. Fig. a shows a simple graph of the observed radio power during an occultation of the Crab Nebula by the Moon (using the Jodrell Bank 25 meter MK II telescope). With the radio telescope fixed on the nebula, at first it will only receive energy from the nebula. Gradually, as the Moon moves across the sky toward the position of the nebula, the signal strength rises as the telescope begins to pick up the additional radiation from the Moon. Then, as the Moon passes in front of the Crab Nebula, the received energy drops. But all the time the signal of the Moon is increasing so while the Crab Nebula is occulted the signal then rises again until it reaches a secondary maximum when the Moon is in the center of the telescope beam. Finally, as the Moon begins to move away we see the whole sequence happening in reverse.

From the periods when the Crab Nebula is fully visible to conversely totally hidden, one can estimate the signal that would have been observed from the Moon alone. This is shown in Fig. b. One can remove the Moon's signal to show how the from the Crab Nebula changes as it went through the occultation. This is shown in Fig. c. One can see that the signal took some time, about 12 minutes or 0.2 hours, to drop to zero. This immediately indicates that the Crab Nebula cannot be a point source, for then the signal would drop instantly, but must have some angular size. This can be estimated with a simple calculation. The Moon moves once around the sky, 360 degrees across, in one lunar month, 28.5 days or 684 hours. Thus the Crab Nebula must be about (0.2/684) x 360 degrees across. That is 0.10 degrees or 6.3 minutes of an arc across. This is a little more than its apparent size (6 x 4 minutes of arc) when observed visually, but it is expected that detection of radio emissions from a somewhat larger region of space would occur.



Radio Occultations with Comet (Ion) Tails

This section will be developed at a later time. However, radio occultations through comet tails occur and have been studied to reveal information on the comet. See the following references:

- Radio Observations of PKS2314+03 During Occultation by Comet Halley, S.K. Alurkar, R.V. Bhonsle & A.K. Sharma, NATURE VOL 322 31JULY, 1986
- Occultation of the Radio Source 2019+098 (3C411) by Comet 1983e (Sugano-Saigusa-Fujikawa, by S. Ananthakrishnan & Dilip G. Banhatti, Radio Astronomy Centre (TIFR), Ooty and Bangalore [1983]
- Plasma Distribution of Comet ISON (C2012 S1) Observed using the Radio Occultation Method, Tomoya Iju, Shinsuke Abe, Munetoshi Tokumaru, Ken'ichi

Fujiki, Solar –Terrestrial Environment Laboratory, Nagoya Univ., Japan, and Dept. of Aerospace Engineering, Nihon Univ., Japan

Radio Occultations by Planets

This section will be developed at a later time. However, the paper "Forthcoming Mutual Events of Planets and Astrometric Radio Sources" by Z. Malkin, V. L'vov, S. Tsekmejster, Pulkovo Observatory, St. Petersburg, Russia, provides information on upcoming radio occultations through 2033.

Table 1. Occultations of astrometric radio sources by planets

Planet	Date, UT Y M D	Source	Elongation, deg
Venus	2012 12 24.4	1631–208	23W
Mercury	2014 07 30.2	0750+218	11W
Venus	2015 08 06.8	0947+064	15E
Jupiter	2016 04 10.4	1101+077	144E
Venus	2020 01 16.7	2220–119	38E
Venus	2020 07 17.7	0446+178	42W
Mercury	2022 11 14.7	1529–195	4E
Jupiter	2025 09 18.6	0725+219	65W
Mercury	2027 03 21.7	2220–119	27W
Saturn	2028 10 24.8	0223+113	173W
Mercury	2029 01 14.3	1958–179	5E
Venus	2029 02 28.2	2221–116	6W
Mercury	2029 04 16.1	0243+181	19E
Mercury	2029 12 27.9	1858–212	8E
Mercury	2030 02 27.6	2208–137	9W
Jupiter	2033 02 04.2	2104–173	1W

For information purposes, the angular diameter of some objects are give:

Celestial Body	Angular Diameter
Sun	31.6′ – 32.7′
Moon	29.3′ – 34.1′
Venus	9.565″ – 66.012″
Jupiter	29.800″ – 50.115″
Saturn	14.991″ – 20.790″
Mars	3.492″ – 25.113″
Mercury	4.535″ – 13.019″
Uranus	3.340″ – 4.084″
Neptune	2.179″ – 2.373″
Ceres	0.330″ – 0.840″
Vesta	0.20" – 0.64"
Pluto	0.063″ – 0.115″
Betelgeuse	0.049″ – 0.060″
Alpha Centauri A	0.007″

Sirius	0.005936″
Proxima Centauri	0.001″

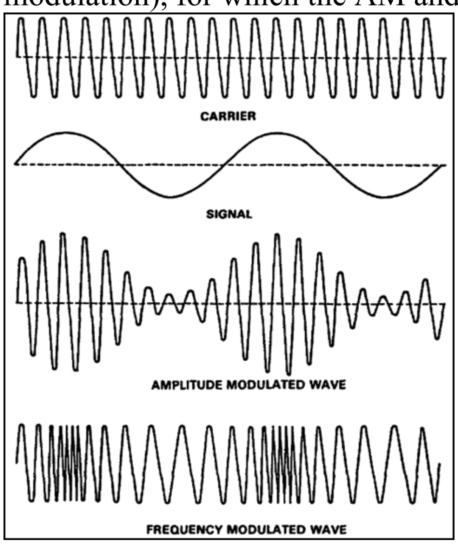
Acronyms/ Glossary

Abscissa: an abscissa is the perpendicular distance of a point from the y - axis.
Angular diameter: The angular diameter or apparent size is an angular measurement describing how large a sphere or circle appears from a given point of view. In the vision sciences it is called the visual angle. For a small circular source, one can compute the solid angle as $\Omega = (\text{angular diameter} * \pi/180°)^2 \pi/4$, which is often given by this approximate formula: $\Omega = (\text{angular diameter} * \pi/180°)^2$
Angular resolution: Angular resolution (θ) of a telescope can be calculated using the wavelength of light or radio waves (λ) the telescope is being used to observe, and the diameter (D) of the telescope. θ = 2.5 x 105 x λ /D, where θ is in arcseconds and λ and D are in meters
Angular size: The angle subtended by an object on the sky. The angle may be measured in units of radians, or in units of degrees, arc minutes (1 degree = 60 arcminutes), and arc seconds (one arc minute = 60 arc seconds). For example, the angular size of the moon in the sky is 30 arc minutes.
AO: Arecibo Occultation
Arc minute: A measure of angular separation, - one sixtieth of a degree.
Arc second: Another measure of angular separation, - one sixtieth of an arc minute. (1/3600th of a degree.)
Bandwidth: The difference between the highest and lowest frequencies to which a receiver is sensitive.
Beam (main): The central peak of the power pattern between the first minima is called the *main beam*. The smaller secondary peaks are called *sidelobes*.
Beamwidth: The angle within which an antenna receives radio waves. The beam diameter or beam width of an electromagnetic beam is the diameter along any specified line that is perpendicular to the beam axis and intersects it.
Beamwidth (half-power): The angle across the main lobe of an antenna pattern between the two directions at which the antenna's sensitivity is half its maximum value at the center of the lobe.
Bessel's method: Bessel's equation arises when finding separable solutions to Laplace's equation and the Helmholtz equation in cylindrical or spherical coordinates. Bessel functions are therefore especially important for many problems of wave propagation and static potentials.
Beating: When two waves of different frequency approach, the alternating constructive and destructive interference causes is called "beating" or producing beats.
Class II radio source: Fanaroff-Riley Class I (FR-I) sources have their low brightness regions further from the central galaxy or quasar than their high brightness regions. Fanaroff-Riley Class II (FR-II) is made up of luminous radio sources with hotspots in their lobes
Contour map (2-dimensional): Contours maps are a common representation of radio sources to depict position and intensity.
CTA: Cherenkov Telescope Array

Convolution process: In mathematics and, in particular, functional analysis, convolution is a mathematical operation on two functions *f* and *g*, producing a third function that is typically viewed as a modified version of one of the original functions, giving the area overlap between the two functions as a function of the amount that one of the original functions is translated.
Declination: One of two coordinates for the celestial sphere, which are analogous to latitude and longitude for the Earth's surface. The declination of an object is how many degrees it is north or south of the celestial equator. The other coordinate is called right ascension, and it is measured eastward from a somewhat arbitrary "prime meridian" on the sky. The "prime meridian" passes through the position of the Sun at the time of the vernal equinox. Thus its position changes slowly over the years, due to the precession of the equinoxes. The position of the celestial poles also changes with precession. Thus, to locate an object from its right ascension and declination, you must also know the date for which those coordinates are valid; that date is called the epoch of the coordinates.
Deconvolution (CLEAN): The Högbom "CLEAN" is a simple algorithm for deconvolving images, that is, it is an algorithm to remove to an extent the smearing in an image due to a finite point-spread function. This algorithm is particularly applicable to making images from radio aperture synthesis array telescopes, where this algorithm (and other closely related) is the standard deconvolution approach.
Dicke type receiver: A Dicke-type receiver is configured to suppress variation in the detection level due to time and temperature variations of the gain of the receiver.
Dielectric constant: the dielectric constant relates to the permittivity of the material. Permittivity is a quantity that describes the effect of a material on an electric field: the higher the permittivity, the more the material tends to reduce any field set up in it.
Diffraction Fringe: Blurred fringe surrounding an image caused by the wave properties of light. No detail smaller than the fringe can be seen.
Diffraction pattern: Diffraction refers to various phenomena, which occur when a wave encounters an obstacle or a slit. In classical physics, the diffraction phenomenon is described as the interference of waves according to the Huygens Fresnel principle. These characteristic behaviors are exhibited when a wave encounters an obstacle or a slit that is comparable in size to its wavelength. Diffraction occurs with all waves, including sound waves, water waves, and electromagnetic waves such as visible light, X-rays and radio waves. Diffraction pattern is
the distinctive pattern of light and dark fringes, rings, etc, formed by diffraction
Double-lobed Radio Source: A galaxy that emits radio energy from two regions located on opposite sides of the galaxy.
Epoch: The coordinates commonly used for the celestial sphere, which are analogous to latitude and longitude for the Earth's surface, are called right ascension and declination. The "prime meridian" of this system passes through the position of the Sun at the time of the vernal equinox. Thus its position changes slowly over the years, due to the precession of the equinoxes. The position of the celestial poles also changes with precession. Thus, to locate an object from its right ascension and declination, you must also know the date for which those coordinates are valid; that date is called the epoch of the coordinates.
Fan beam: Fan beam describes a pattern of matter or energy emitted from a transmitter, particularly a radio wave transmitter. Fan beams, applied in radio astronomy, are more effective than tight pencil beams in scanning deep space for radio signals.

Fast Fourier Transform (FFT): A Fourier Transform is the mathematical operation that takes measurements made with a radio interferometer and transforms them into an image of the radio sky. The Fast Fourier Transform is technique used by computer programs that allows the Fourier Transform to be computed very quickly.
Flux: The rate of transfer of fluid, particles, or energy across a given surface. The flux unit or jansky (symbol Jy) is a non-SI unit of spectral flux density, or spectral irradiance, equivalent to 10^{-26} watts per square metre per hertz.
Flux density: the flux (or more accurately: the flux density) *F* (or often: *S*) is the power per unit frequency interval that passes through a surface of unit area. Thus the power density received by our antenna is $P = F * A / 2,$ where *A* is the (effective) cross section of the antenna dish. There is a reduction by a factor 2, because we observe in horizontal or vertical polarization only.
Flux Unit (FU): The flux unit or jansky (symbol Jy) is a non-SI unit of spectral flux density, or spectral irradiance, equivalent to 10^{-26} watts per square metre per hertz.
Frequency: Number of wave vibrations per second; 1 Hertz is one cycle per second (e.g., 1420 MHz = 1,420,000,000 vibrations per second). Frequency may also be denoted by the lowercase letter Nu, ν
Frequency (central): the center frequency of a filter or channel is a measure of a central frequency between the upper and lower cutoff frequencies.
Frequency band: A band is a small section of the spectrum of radio frequencies
Fresnel zone: Fresnel zones are used by propagation theory to calculate reflections and diffraction loss between a transmitter and receiver. Fresnel zones are numbered and are called ‘F1’, ‘F2’, ‘F3’ etc. There are an infinite number of Fresnel zones, however, only the first 3 have any real effect on radio propagation. Why is this important? The receive antenna cannot differentiate between a main and reflected signal. They are both on the same frequency. It receives both main and reflected signals. It also receives any other signals within its designed frequency range. When an antenna receives a main signal and a reflected signal, the 2 signals will combine and add together at the antenna. If they are 360º shifted (in phase), there is no issue. However, if the signals are 180º apart (opposite phase), they will cancel and the receiver will receive nothing.
Gaussian profile: Gaussian function, often simply referred to as a Gaussian, is a function of the form: $f(x) = a \exp\left(-\frac{(x-b)^2}{2c^2}\right)$ for arbitrary real constants *a*, *b* and *c*. The graph of a Gaussian is a characteristic symmetric "bell curve" shape. The parameter *a* is the height of the curve's peak, *b* is the position of the center of the peak and *c* (the standard deviation, sometimes called the Gaussian RMS width) controls the width of the "bell". Gaussian functions are widely used in statistics where they describe the normal distributions, in signal processing where they serve to define Gaussian filters, in image processing where two-dimensional Gaussians are used for Gaussian blurs, and in mathematics where they are used to solve heat equations and diffusion equations and to define the Weierstrass transform.
Generalized least square: In statistics, generalized least squares (GLS) is a technique for estimating the unknown parameters in a linear regression model.
Interference: For radio telescopes, this typically means unwanted signals, noise, or static. It also describes the result of combining the signals that two telescopes receive when observing the same source, which results in a pattern of oscillating values or "fringes" that depends on the separation of the two telescopes.

Interferometer: A radio telescope consisting of two or more antennas at some distance from one another. It uses the phenomenon of interference in order to increase the effective resolving power of the antennas.
Interferometric visibility: (also known as "interference visibility" or "fringe visibility" or just "visibility") quantifies the contrast of interference in any system that has wave-like properties, such as optics, or electrical signals. Generally, two or more waves are combined and as the phase between them is changed (e.g. in an interferometer) the power or intensity of the resulting wave oscillates (forming an interference pattern).
Intensity (radiant, emission): I, is a measure of the intensity of electromagnetic radiation. It is defined as power per unit solid angle. The SI unit of radiant intensity is watts per steradian. The intensity including *all* possible frequencies, the total intensity can be obtained by integrating over all frequencies.
Isophotes of the optical continuum: a curve on a chart joining points of equal light intensity from a given source.
Lobe (main): In a radio antenna's radiation pattern, the main lobe, or main beam is the lobe containing the maximum power. This is the lobe that exhibits the greatest field strength.
Lobe (side): In antenna engineering, side lobes or sidelobes are the lobes (local maxima) of the far field radiation pattern that are not the main lobe.
MSH: Mills, Slee, Hill - Catalog of Radio Sources
Modulation: The method by which audio, (information), is impressed on a radio signal is called modulation. To modulate a radio wave is to add information to it that can be received on a receiver for some useful purpose. There are two types of modulation that most people are familiar with, AM (amplitude modulation), and FM, (frequency modulation), for which the AM and FM broadcast bands were named.



Source: http://debj150.blogspot.com/

Jansky: A unit of measurement of flux density equal to 10^{-26} Watts / meter^2 / Hz, named after the radio astronomy pioneer Karl Jansky.
Mc/s: Megacycles per second
Millimeter wavelength occultations: Extremely high frequency (EHF) is the ITU designation for the band of radio frequencies in the electromagnetic spectrum from 30 to 300 gigahertz, above which electromagnetic radiation is considered

to be low (or far) infrared light, also referred to as terahertz radiation. Radio waves in this band have wavelengths from ten to one millimetre, giving it the name millimetre band or millimetre wave, sometimes abbreviated MMW or mmW.

Minimum detectable signal: Minimum detectable signal (MDS) in a radio receiver is the smallest signal power that can be received at its input, processed by its conversion chain and demodulated by the receiver, resulting in usable information at the demodulator output. The MDS is also known as the noise floor of the system. It is mathematically defined as the input signal power required to give some specified output SNR. $P_{min} = k\ T\ B\ F\ (S/N)_{min}$, , Where P_{min} = Minimum Detectable Signal; k = Blotzmann's Constant = 1.38×10^{-23} (Watt*sec/°Kelvin); T = Temperature (°Kelvin); B = Receiver Bandwidth (Hz); F = Noise Factor (ratio), Noise Figure (dB); $(S/N)_{min}$ = Minimum Signal to Noise Ratio

Modulation index M: Modulation index indicates how much the carrier's amplitude can change due to modulation. For example, we have a 1V carrier wave: With 50% modulation, the carrier's amplitude can be changed from 1V to 0.5V

Nautical almanac: A nautical almanac is a publication describing the positions of a selection of celestial bodies for the purpose of enabling navigators to use celestial navigation to determine the position of their ship while at sea. Almanac data is now available online from the US Naval Observatory.

Noise: The effects produced by random electrical fluctuations in radio receivers. These tend to conceal or distort the effects of true celestial radio power, which also has the character of noise.

Non-thermal emission: Electromagnetic radiation produced by synchrotron radiation, maser line emissions from atoms and molecules, or the mechanisms not related to temperature.

Ordinate: (in a system of coordinates) the y -coordinate, representing the distance from a point to the horizontal or x -axis measured parallel to the vertical or y -axis.

Parametric amplifier: a sensitive, low-noise amplifier of high-frequency or microwave radio waves that utilizes an inductor or capacitor whose reactance varies periodically at a similar frequency

Phase: The absolute value of φ has no physical significance because you can measure φ from any reference point you want. However the difference in φ between two wave functions has a very important physical meaning because it determines how the waves will interfere.

Polarization: The action or process of affecting radiation and especially light so that the vibrations of the wave assume a definite form.

Polarization (degree of): Degree of polarization (DOP) is a quantity used to describe the portion of an electromagnetic wave that is polarized. A perfectly polarized wave has a DOP of 100%, whereas an unpolarized wave has a DOP of 0%.

Pumping mechanism:: pumping is the act of energy transfer from an external source.

QSO: Quasi-Stellar Objects (QSO)

Radio lobe galaxies: Strong radio emitters. The radio signal doesn't come from the center of the galaxy but from two ``lobes'' on the sides of the galaxy. The radio lobes do not emit visible light. The radio lobes are big, hundreds of kly. The model of a supermassive black hole would appear to be a good guess. The jets from the accretion disk shoot out beyond the galaxy and eventually radiate at radio wavelengths.

Receiver: An electronic device that amplifies, detects, and gives a measure of the intensity of radio signals.
Resolution: The ability of a telescope to show detail. Also known as resolving power. One common way to describe the resolution of a telescope is to state the minimum angular separation at which a double star, whose two components are fairly bright and have very nearly the same brightness, can be distinguished as two separate stars.
Right ascension: The equatorial coordinate specifying the angle (usually specified in hours, minutes and seconds), measured eastward along the celestial equator from the vernal equinox to the hour circle passing through an object in the sky.
Rms error: root mean square error. A measure of the difference between locations that are known and locations that have been interpolated or digitized. RMS error is derived by squaring the differences between known and unknown points, adding those together, dividing that by the number of test points, and then taking the square root of that result.
Scintillations (Radio): Stars twinkle in optical light because they have very small angular diameters, milli-arcseconds or less, and hence suffer interference as the light passes through the Earth's turbulent atmosphere. Planets don't, since they subtend a very large angular diameter, many-arcseconds or more, and hence they lose their twinkle. Much the same applies to radio sources as their radio light passes through the turbulent ionized interstellar medium of our Galaxy, where the "cells" of turbulence allow several ray paths to interfere. If the quasar is small enough, then it will twinkle, if it's too large then there will be no twinkling. Trouble is, radio quasars need to be microarcseconds in angular size to twinkle, and that's pretty small.
Signal-to-noise ratio: (often abbreviated SNR or S/N) is a measure used in science and engineering that compares the level of a desired signal to the level of background noise.
SiO Masers: The radio radiation detected in some lines of certain astronomical molecules is attributed to the natural occurrence of the maser phenomenon (microwave amplification by stimulated emission of radiation), the same as that produced by artificial means in laser devices. three "classical" maser molecules - OH, H_2O, and SiO.
Spectral index: the spectral index of a source is a measure of the dependence of radiative flux density on frequency. Given frequency ν and radiative flux S, the spectral index α is given implicitly by $S \propto \nu^{\alpha}$.
Spectrum: A plot of the intensity of light at different frequencies. Or the distribution of wavelengths and frequencies.
SSB: Single Side band Single sideband is more properly called a "mode" like AM or FM. It is a very efficient method of superimposing information on a radio wave and the transmission of that radio wave.
Steradian: The steradian (symbol: sr) is the SI unit of solid angle. It is used to describe two-dimensional angular spans in three-dimensional space, analogous to the way in which the radian describes angles in a plane.
Strip integrated brightness distributions: The three-dimensional structure of extragalactic sources is usually inferred from the observations of the angular size and bright ness distribution projected onto the plane of the sky. Often only the brightness distribution in one dimension is determined. The data on brightness distributions are obtained by one of four common procedures, one being lunar occultations.
Thermal emission: Radiation emitted due to an object's temperature (e.g., blackbody radiation) or by an ionized gas.

Time constant: the time constant, usually denoted by the Greek letter τ (tau), The time constant is also used to characterize the frequency response of various signal processing systems including receivers.
VLBI: Very-long-baseline interferometry (VLBI) is a type of astronomical interferometry used in radio astronomy. In **VLBI** a signal from an astronomical radio source, such as a quasar, is collected at multiple radio telescopes on Earth.
Wavelength: The distance between two adjacent crests of a wave motion. For electromagnetic radiation, the product of frequency and wavelength is equal to the speed of light. Wavelength is commonly designated by the Greek letter *lambda* (λ)
Other Useful Information

Astronomical Source Catalogues

- The Dixon Master List of Radio Sources (Version 43, dated November 1981), which contains flux densities for known radio sources detected at a variety of frequencies. The Master List of Radio Sources was prepared by combining about thirty catalogs of radio sources that were available as of that date into a common format.
- 2002ApJS..143....1McMahon+ (Submitted on 18 Oct 2001) accepted 2002 June 30, Optical Counterparts for 70,000 Radio Sources: APM Identifications for the FIRST Radio Survey, Authors: Richard G. McMahon, Richard L. White, David J. Helfand, Robert H. Becker
- PKSCAT: Parkes Catalogue
- MRC: The original Molonglo 408MHz Reference Catalogue , The Sydney University Molonglo Sky Survey (SUMSS) is a radio imaging survey of the sky south
- The NRAO VLA Sky Survey (NVSS) is a 1.4 GHz continuum survey covering the entire sky north of -40 deg declination. A detailed description appears in the 1998 May issue of The Astronomical Journal (Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693).
- The Third Cambridge Catalogue of Radio Sources (3C) is an astronomical catalogue of celestial radio sources detected originally at 159 MHz, and subsequently at 178 MHz.
- Palomar Sky Survey

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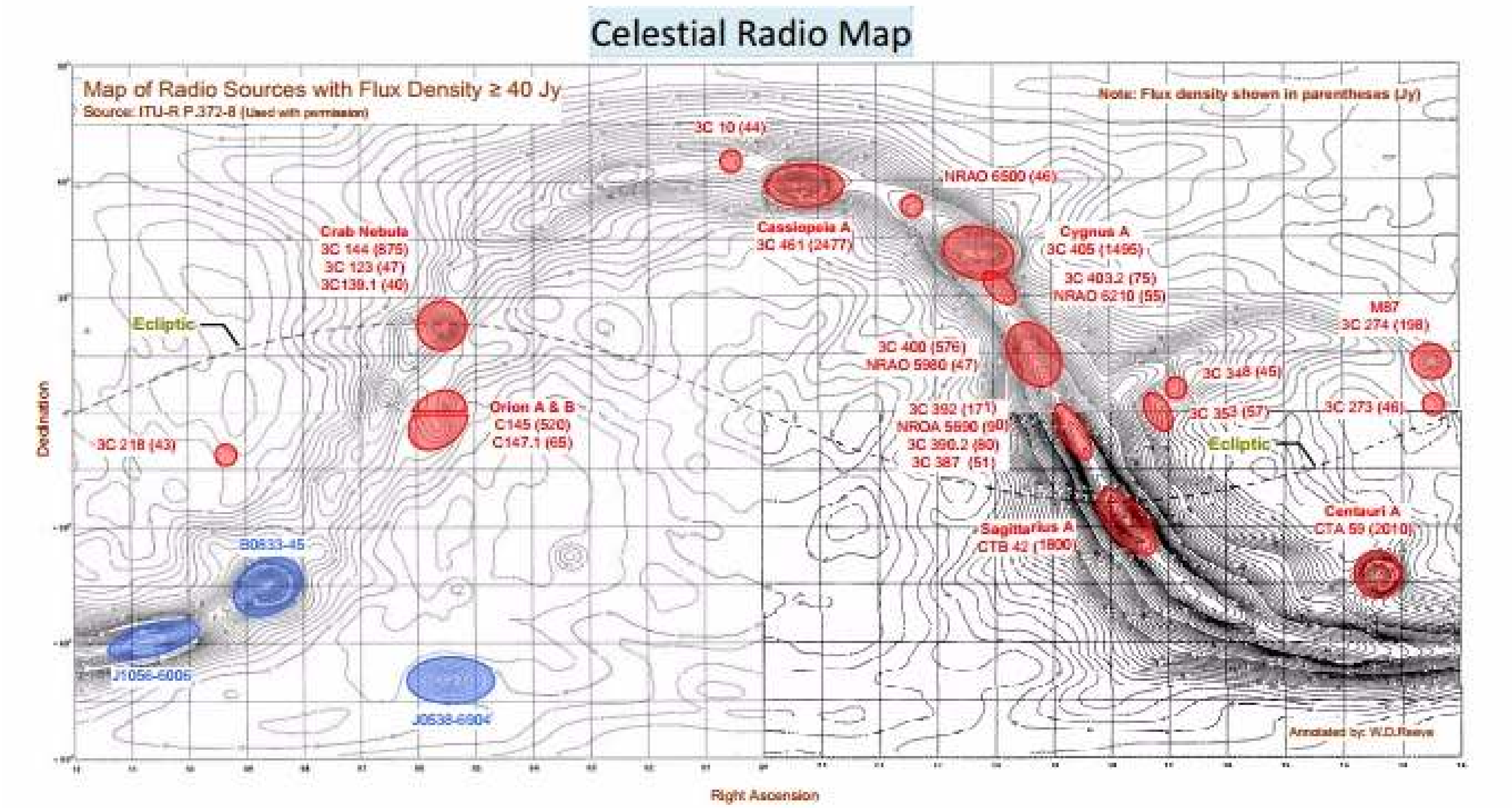
Appendix

Important Celestial Radio Sources By: Whitham D. Reeve
http://www.reeve.com/Documents/RadioScience/CelestialRadioSources.pdf
The list of celestial radio sources presented below was obtained from National Radio Astronomy Observatory (NRAO) library.

Object Name	RA (hh mm ss)	Dec (dd mm ss)	Epoch	Flux Density (Jy)	Frequency (MHz)	Other Name
3C 461	23 23 24	58 48 54	2000	2477	1,420	SNR-Cassiopeia A
CTA 59	13 22 28	-42 46 00	1950	2010	960	Cent A NGC5128
CTB 42	17 42 09	-28 50 00	1950	1800	960	Sag A Galactic Nucleus
3C 405	19 59 28	40 44 02	2000	1495	1,420	D Galaxy-Cygnus A
3C 144	05 34 32	22 00 52	2000	875	1,420	SNR-Crab Nebula
3C 400	19 23 42	14 30 33	2000	576	1,420	
3C 145	05 35 17	-05 23 28	2000	520	1,420	Emission Nebula-OrionA
3C 274	12 30 49	12 23 28	2000	198	1,420	Elliptical Galaxy-M87
3C 392	18 56 06	01 18 00	2000	171	1,420	SNR
NRAO 5690	18 35 00	-07 20 00	2000	90	1,420	
3C 390.2	18 47 58	-01 56 43	2000	80	1,420	
3C 403.2	19 54 12	32 54 00	2000	75	1,420	
3C 147.1	05 41 43	-01 54 17	2000	65	1,420	Emission Nebula-OrionB
3C 353	17 20 28	-00 58 47	2000	57	1,420	D Galaxy
NRAO 6210	20 01 42	33 17 00	2000	55	1,420	
3C 387	18 41 00	-05 16 00	2000	51	1,420	
3C 123	04 37 04	29 40 14	2000	47	1,420	Galaxy
NRAO 5980	19 10 19	09 04 07	2000	47	1,420	
3C 273	12 29 07	02 03 09	2000	46	1,420	Quasar
NRAO 6500	21 12 21	52 28 58	2000	46	1,420	
3C 348	16 51 08	04 59 34	2000	45	1,420	D Galaxy
3C 10	00 25 13	64 08 42	2000	44	1,420	SNR-Tycho's Supernova
3C 218	09 18 06	-12 05 44	2000	43	1,420	D Galaxy
3C 139.1	05 22 25	33 29 55	2000	40	1,420	Emission Nebula
NRAO 6620	21 29 24	50 48 00	2000	37	1,420	
NRAO 6020	19 15 42	11 02 00	2000	35	1,420	
3C 398	19 11 09	09 06 24	2000	33	1,420	
NRAO 5720	18 38 15	-06 47 37	2000	30	1,420	
3C 153.1	06 09 36	20 29 19	2000	29	1,420	Emission Nebula
NRAO 1560	04 04 50	51 22 18	2000	26	1,420	
3C 147	05 42 36	49 51 07	2000	23	1,420	Quasar
3C 295	14 11 21	52 12 09	2000	23	1,420	D Galaxy
3C 391	18 49 22	-00 55 21	2000	21	1,420	
NRAO 1650	04 11 05	51 09 08	2000	19	1,420	
3C 161	06 27 10	-05 53 05	2000	19	1,420	
NRAO 5790	18 46 07	-02 43 24	2000	19	1,420	
3C 270	12 19 23	05 49 33	2000	18	1,420	Elliptical Galaxy
3C 48	01 37 41	33 09 35	2000	16	1,420	Quasar
3C 111	04 18 21	38 01 36	2000	15	1,420	
3C 286	13 31 08	30 30 33	2000	15	1,420	Quasar
NRAO 5840	18 53 20	01 14 54	2000	15	1,420	
3C 84	03 19 48	41 30 42	2000	14	1,420	Seyfert Galaxy
3C 196	08 13 36	48 13 03	2000	14	1,420	Quasar
3C 380	18 29 32	48 44 47	2000	14	1,420	Quasar
NRAO 5890	19 01 48	01 46 53	2000	14	1,420	
3C 396	19 03 58	05 22 30	2000	14	1,420	
3C 397	19 07 40	07 08 39	2000	14	1,420	
3C 409	20 14 28	23 34 58	2000	14	1,420	
3C 33	01 08 53	13 20 14	2000	13	1,420	Elliptical Galaxy
3C 20	00 43 09	52 03 34	2000	12	1,420	Galaxy
NRAO 5670	18 32 00	-02 04 00	2000	12	1,420	
3C 390.3	18 42 09	79 46 17	2000	12	1,420	N Galaxy
3C 433	21 23 45	25 04 18	2000	12	1,420	D Galaxy
3C 434.1	21 25 04	51 52 52	2000	12	1,420	
3C 279	12 56 11	-05 47 22	2000	11	1,420	Quasar
NRAO 6070	19 18 06	12 12 00	2000	11	1,420	
3C 452	22 45 49	39 41 16	2000	11	1,420	Elliptical Galaxy
3C 454.3	22 53 58	16 08 54	2000	11	1,420	Quasar
NRAO 6010	19 14 20	11 09 06	2000	10	1,420	
3C 410	20 20 07	29 42 14	2000	10	1,420	


Celestial Radio Map
Map of Radio Sources with Flux Density ≥ 40 Jy
Source: ITU-R P.372-8 (Used with permission)
Note: Flux density shown in parentheses (Jy)
3C 10 (44)
Cassiopeia A
3C 461 (2477)
NRAO 6500 (46)
Cygnus A
3C 405 (1495)
3C 403.2 (75)
NRAO 6210 (55)
Crab Nebula
3C 144 (875)
3C 123 (47)
3C139.1 (40)
Ecliptic
Orion A & B
C145 (520)
C147.1 (65)
3C 218 (43)
3C 400 (576)
NRAO 5980 (47)
3C 392 (171)
NROA 5690 (90)
3C 390.2 (80)
3C 387 (51)
Sagittarius A
CTB 42 (1800)
M87
3C 274 (198)
3C 348 (45)
3C 353 (57)
3C 273 (46)
Ecliptic
Centauri A
CTA 59 (2010)
B0833-45
J1056-6005
J0538-6904
Annotated by: W.D.Reeve
Declination
Right Ascension

Disclaimer Suggestions Subsection

This subsection includes comments, suggestions, and peer reviews for improving this protocol. The reason for this is to allow a protocol to become a living document and be posted, rather than stagnate in obscurity until a volunteer is found to enhance the protocol. SARA members will always have ideas for improvement. To make improvements or offer comments, contact the Analytical SARA Section Coordinator.

Comments by Ed Harfmann on 7/7/2015

1) Are you thinking of this as a page online or a document to pull down? If a page, then this becomes a subsection page from the Analytical. As a document, you've assumed a MS Word reader. (Not a bad assumption, but an assumption.)
2) As a standalone document, the acronyms/glossary is a must. As a web page, a global table shared by all sections might be called for? Not sure.
3) The references are great. This gives me plenty of reading material (if I can find them). I like a mixture of online and print publications. I like the titles as listed as they give me search keys for Google/…
4) I LOVE the appendix. The table gives everything that I need to help start deciding what to try and whether I've got a chance of doing it (RA/Dec & Flux). The map gives a quick glance of the same basic information.
5) Thought – Should parts of this (or possibly the whole thing) be a Wikipedia article? My thought here is what if this paper were a Wikipedia article and the link on the Analytical section took you to it. You might get better exposure. Also allow for others to comment/edit the document over time more easily. (Not sure if that is a good or bad thing.)
6) Radio Occultations by X. I like that they are mentioned. (Opens up ideas thinking beyond the Moon.) I like the references to papers and the chart. Gives me the idea of other ways to think/do this type of observation.

Now for the questions, problems, omissions…

1) The background says "The protocol was developed to assist amateur astronomers quickly learn the basics of radio occultation methodologies without having to research numerous professional journal papers." I'll take this to mean "The protocol was developed to assist amateur astronomers quickly learn the basics of radio occultation methodologies by directing them to professional journal papers without false starts." I could read the first as saying the details are summarized so that they don't have to read the papers, but that is not what is here in the protocol.
2) In my mind, this technique (occultation) was one of the major keys to RA becoming a serious tool for astronomy. (Specifically the quasar 3C 273 being shown to be definitively outside our galaxy and not a strange local star.) As a scientist, this makes me think of reproducing a classic experiment. I'd suggest adding at least part of that history/reference to this protocol.
3) For the technique references (Scheuer and von Hoemer), I would have expected to see the title in the reference below. If the referenced page disappears, finding which document you had in mind becomes much more difficult (especially if it is

pay walled). IMO, web links should provide enough keywords on/near the link so that the page could be found via Google/… should the page move or be deleted.

4) I don't have a good idea of the difficulty or equipment required. This obviously depends upon the target and the occulting object, but I think there should be a feel for the technique and technical expectations required to give this a try, e.g. this type of observation requires the user to have the following basic abilities:
   - Accurate time base
   - Sensitive antenna such that integration time required for the object does not cause issues.
   - High school mathematics? Calculus? (This looks like calculus to me.)
   - Ability to observe HI line

   As a novice, I don't have a good feel for what is a logical progression from a $200 cheap telescope to get to this point of observing ability. What skills are needed to build up? What techniques? What equipment?

5) Sample format of data – This looks like a table of many sources and summary data. (No problem with that per say.) I would expect an observer to submit one entry at a time. The need for a table looks overwhelming. It might be what we use to store the data, but not how the observer will provide it. Would it make sense to allow for the additional of the raw input table for reference (assuming we have the space?) Having the raw data and the telescope specs (table 2) should allow anyone to reconstruct the resulting summary data. If the submitter made a mistake in the calculations, then the summary record is wrong. If the raw data exists, then the error can be fixed and the summary amended.

6) I'd suggest that the additional information be formalized into another table or multiple tables. Tables 1 and 2 are publicly visible. Table 3 – with contact information – is private. Each contact receives an ID of some type, which would be visible in tables 1 & 2. Only when someone wishes to query for more information would the contact be given the request and prompted to respond. Alternately, the name and ID are exposed in the other tables. Other contact information is hidden (to prevent spam or other abuses) unless needed. (Sorry, ex-database vendor coming out.) The more the fields are standardized, the easier it is to find data. Free form is great until you start to search for data.

7) As an inexperienced observer, I see the various sections, the various observations, but I don't see a clear way to build technique to the point of my being able to do this type of observation or whether there are any prerequisites that I may have no hope of overcoming. Knowing what questions actually to ask are often more important than having a list of basic answers. (Follow I65 south to … is a lot better than head south until you find it.)

8) All that being said, I think I'll definitely stick with an excellent draft document. It is much better than I could possibly have done. My comments are mainly minor improvements in my opinion.