HamSCI - Ham Radio Science Citizen Investigation - Connecting Communities

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Good morning. I'm Gwyn Griffiths, callsign G3ZIL. I'm grateful to the RSGB for this opportunity to talk to you about a collective called HamSCI: the Ham Radio Science Citizen Investigation. My talk will cover several areas of amateur radio and space physics, pinpointing how radio amateurs play important roles in HamSCI's activities and outputs. Most importantly, I'll explain how each of you can join in.

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I was licenced as GW3ZIL in 1970, while very active in those days, amateur radio took a back seat during my career as an oceanographer.

Little did I realise those 40 years were merely an apprenticeship ahead of fascinating parallels and challenges in studying radio waves and the ionosphere.

Working clockwise from top left, the International Space Station orbits within the ionosphere, its optical cameras capture the magnificence of the aurora. Top right is another ISS image, using microwave synthetic aperture radar it shows a train of waves propagating into the Mediterranean. That surface pattern was caused by waves over 50 metres high under the sea surface, shown bottom right on this sonar image I took in 1998.

The incoming tide triggered that wave packet. A geomagnetic storm this July triggered a wave packet in the ionosphere – the response, shown lower left as Doppler shift on 10 MHz over a 1765 km path, is a rich source of information and questions – and a great example of why I'm involved with HamSCI

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HamSCI was founded in 2016 by Dr. Nathaniel Frissell, W2NAF.

It is not a formally defined organization – but a loose, yet effective, collaboration between members of the scientific community, mostly, but not entirely, university researchers and graduate students, licenced radio amateurs and listeners with receive-only stations from VLF upward.

Amateurs play a vital role - as citizen scientists - volunteers - who enjoy combining their passion for radio with contributing to a better understanding of space physics.

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Here's a definition of citizen science from the Oxford dictionary: It *is* Scientific work. While I have no qualifications in space physics, I have skills that prove useful. Mine are in data analysis and data presentation. For others it may be circuit design or construction, or coding software, or, indeed, by simply operating on the bands.

There are dozens of citizen science projects utilizing volunteers with many different skills and interests. In the USA NASA is a big supporter of citizen science programmes, providing encouragement and funding. Here are some examples, and a link to find out more.

At HamSCI, we feel radio amateurs make ideal citizen scientists because of our training and technical abilities. And, to be clear, while led from the US, HamSCI is a global community. All volunteers are welcome.

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The collaboration between scientists and citizen scientists is clear throughout our website, hamsci.org. It contains a lot of information, covering people, projects, findings, workshops, technical papers, presentations, posters and more.

If you look though our website for a common thread, you'll find one: A passionate interest in the Earth's ionosphere, the region of the Earth's atmosphere responsible for propagating radio signals over long distances. That's where you would all recognize the connection between HamSCI and the amateur radio world.

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HamsSCI offers projects of varying complexity. Explore our website - see what interests you.

If it is building, check out the Personal Space Weather Station projects for receivers and a magnetometer. It is coding, there are many examples of citizen science contributions to Digital Signal Processing, data acquisition and databases. By operating you can, unwittingly, contribute to crowd-sourced data, or you can contribute to special HamSCI measurement events such as for the recent solar eclipses. Or, you can help analyse rich data sets from the amateur and professional communities.

Many HamSCI projects are funded through grants from organizations such as the US National Science Foundation, NASA and the Amateur Radio Digital Communications Foundation.

When it has grant money, HamSCI can supply equipment to host stations at little or no cost. Check out the Personal Space Weather Station pages for current opportunities.

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HamSCI is proud to have supported the development by radio amateurs of low cost hardware and software that is scientifically useful to ionospheric studies. The GRAPE 1 receiver, for instance, can be built and configured by following detailed instructions on the HamSCI website.

Each version of the GRAPE receives standard time and frequency stations, such as WWV, WWVH or CHU. Using a GPS disciplined oscillator ensures high accuracy for the received beat note (typically one milliHertz at 10 MHz). From the Doppler shift of the beat note the height of the ionosphere can be monitored, as I'll show later.

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Experience with the single frequency GRAPE-1 receiver showed it would be advantageous to measure Doppler shift simultaneously on three bands. For example, on some paths, 10 MHz might not be open at critical times, such as dusk and dawn. While based on the GRAPE 1 extensive use of surface mount components means that version 2 comes preassembled. Grant funding to Nathaniel

Frissell W2NAF enabled 30 to be deployed to volunteers ahead of the April 2024 total eclipse experiment.

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Here's a great example of a HamSCI amateur radio member – and a good friend – Rob Robinett AI6VN coming up with a radical receiver solution. Rob realised that the recently available RX888 Mk2 Software Defined Receiver – despite having no on-board signal processing – nay, because it had no on-board processing, could be an awesome simultaneous, multichannel GRAPE and digital modes receiver. All he needed was software to handle the two gigabits per second data output over USB3.

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Rob knew where the solution could be found – in the highly capable, but under-recognised software from another radio amateur – Phil Karn KA9Q.

Here's a simplified block diagram. 20 milliseconds of new in-phase and quadrature 16-bit samples and those from the previous 5 milliseconds are the input to a Fast Fourier Transform, optimised for speed as the number of samples is a product of low prime numbers. It's as if we have a full-spectrum waterfall with 40 Hz resolution. In software, Phil implements passband filters – there can be hundreds, independent, in parallel – with each filter's frequency domain output routed to an inverse FFT to give a digital wav file output in the time domain.

Each individual channel requires very little CPU – Phil's estimate is 0.7% of one core for each channel.

KA9Q-radio gives us multiple wav files – how do we deal with those?

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Rob had already coded an app, WsprDaemon, that took wav files from multichannel KiwiSDRs, used the wsprd and jt9 decoders from the ubiquitous WSJT-X digital modes package, to report WSPR and FST4W spots to databases. In time for the April 2024 eclipse he, working with Franco K4VZ, added the option to process incoming time station wav files from ka9q-radio, and format as digital_RF files. Digital_RF is a file format devised by researchers at the Massachusetts Institute of Technology's Haystack Radio Astronomy Observatory for radio and radar data, and can be accepted by HamSCI's database.

Subsequently, Rob added the option to decode wav files from ka9q-radio for FT8 and FT4 signals and send to pskreporter. All these channels in parallel, from a single receiver and single PC.

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HamSCI's members design and construction inventiveness has not just been confined to receivers. To make best use of simultaneous multiband receivers we could do with simultaneous multiband transmitters. HamSCI member Paul Elliott WB6CXC came up with the WsprSonde. The current version can transmit digital modes WSPR or FST4W on eight HF bands simultaneously. Each frequency has an output of 1 watt. Depending on the available antenna or antennas, several outputs can be combined into a single antenna, while others may be fed to dedicated antennas. Frequency precision is guaranteed by a GPS disciplined oscillator. After initial setup, no PC or Internet connection is needed, but if present, does provide a useful monitor.

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The Central Control System – in essence the Central Database – for Grape receiver data files, be they from fldigi or digital_rf, is at the University of Alabama, Huntsville. Created by professionals, to a design of Bill Engelke AB4EJ. For intricate details search Liddle, Muscolino and HamSCI.

What matters for this talk is the user-facing website in the title. You'll see a map with active and historic receiver stations. Clicking on an icon brings up its callsign. If you click 'Register your station' – you do not have to be providing data – you can log on to see the list of Observations. Use the Filter to show a list of files meeting your criteria. Each will have one day of data. Click on a line of interest and, as in the image at bottom right, you'll see a plot of the Doppler spectrum – a spectrogram – with Doppler shift on the Y axis and time of day in hours UTC on the X axis. Under the spectrogram is a simple plot of the peak amplitude in linear units within each one-minute interval. This provides an automated, quick-look, useful to see if the data shows features of interest, and if it does, you can download the plot or the data set.

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With over one hundred Grape receivers potentially reporting to the database, it is quite appropriate to think of the HamSCI installations as forming a Personal Space Weather Station **Network**.

The cluster of stations on the west coast and the southwest was very well placed to study the annular solar eclipse of October 2023. And we could not have asked for a better path for the total eclipse in April 2024 – it passed over scores of receivers and four WsprSonde transmitters.

Some of the results I'll show today are from these colour-coded paths.

Although the network back in April was quite good, HamSCI does want to add dozens more PSWS in the under-represented regions of the US and Canada. Dr Frissell, W2NAF, has a new US National Science Foundation grant of over $480,000 starting January 2025 to help make that happen.

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I don't want to give the impression that HamSCI is only about technology; it does encourage operating through various on-air events.

These events have two goals:

First, Creating data for research. Every QSO is a data point (who was transmitting, who received them, when, on which band)

Second, Encouraging getting on the air, communicating, while knowing that, in a small way, you're contributing to a long tradition of amateur radio and studies of the ionosphere.

The best-known HamSCI on-air events are the recent Solar Eclipse QSO Parties, held during the 2023 and 2024 solar eclipses. With nearly 900 entrants the overall QSO and digital modes spots count of nearly 1.9 million is an amazing resource for researchers. You can expect to hear of other HamSCI on-air events in the future.

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Not all of HamSCI eclipse observations involved the ham bands, or even transmitting.

Here are graphs of signal strength from a California Medium Wave listener KE6EE monitoring AM broadcast station KKXA, in Snohomish, Washington State. On the control day, October 13th, on the left, you can see how the signal steadily weakened after sunrise. This is D region absorption increasing as the sun rises. The graph looks much different on eclipse day: The signals grew in strength as the eclipse passed over the western US - a brief period of darkness - which caused the signal to dramatically peak, likely due to the temporary darkness reducing absorption in the D-region.

This eclipse event was led by a HamSCI citizen scientist, Nick Hall-Patch, VE7DXR, assisted by many in the Medium Wave listening community.

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The digital modes from the WSJT-X software suite are very useful to our studies, as is the multichannel KiwiSDR, as used here.

The left graph shows received noise levels on 40 metres for two receiver locations on California's west coast. These noise levels were measured during gaps in FST4W reception. Note the significant peak during the eclipse period. It is, of course, common knowledge that daytime D region absorption affects 40 metres. As absorption reduced due to the eclipse noise from distant sources was seen at a higher level at both sites.

On the right graph, note the 'bump' in signal strength at the time of the eclipse for transmissions from Nevada to Utah on 80 metres. The red data points are for eclipse day, showing clearly the effect of reduced absorption.

Taken together, the past few sides are clear indications that data - captured by radio amateurs, and listeners - reflect changes in signal and noise levels during a solar eclipse.

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Having seen the effect of an eclipse on signal and noise levels using a conventional SDR, let's look at a different variable – Doppler shift – and from the purpose designed Grape1 receiver.

W2NAF's Grape1 records its data in a format originally developed by MIT's Haystack Laboratory for radar research. The format is called DRF, digital_RF.

For all Grapes, once installed, no operator intervention is required. Data is automatically uploaded to the HamSCI Personal Space Weather Station database. Spectrograms that use colour to represent signal level with Doppler shift on the Y-axis and time of day UTC on the X-axis are generated automatically. In this example we see positive Doppler around dawn – as the height of reflection from the F2 layer descends.

The Doppler shift pattern during the eclipse tells us height reflection rose, steadied, and then descended. Let's look at an example in more detail.

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This example is from a Grape WsprDaemon receiver, also from WWV to W2NAF, but at 20 MHz and for the April 2024 total eclipse.

The upper plot is a spectrogram, not the automatic version, but one I generated from downloaded digital_RF data. I've zoomed-in on the eclipse interval.

As the eclipse starts Doppler goes negative: reflection height is rising. There's a swap in sign near the eclipse maximum, 88.5% obscured at the path mid point, and the positive Doppler shows the height of reflection descending.

The problem with the spectrogram is that it is an image, like a waterfall display on its side. It does not give me a time series of Doppler shift values, which is what I really need.

The lower plot shows the results of two different algorithms for finding those Doppler values. Details are for another time, but you'll see that the autocorrelation algorithm, the black dots, while dead easy to code, sometimes gets it wrong. A more intricate algorithm where I fit 'Mexican Hat' wavelets to spectra from a Fast Fourier Transform every minute, the red circles, does a better job, but not quite 100% of the time.

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With some hand waving I've suggested in the last two slides that the Doppler shift we've measured tells us height of reflection. I set out the maths, some simple geometry and algebra, to get from Doppler shift to reflection height in an article in August 2024's RadCom. The steps are summarised here.

For this plot I got the first value for height h from a ray trace simulation: 173 km. That's our starting point on the left.

First, there is hardly any difference in the height variation between the two algorithms until the very end. The inference from the Doppler shift results is that the height of reflection at 20 MHz rose by 57 km, stopped, and then fell back about 45 km as the eclipse passed.

Second, the shape of the rise and fall is very close to the blue line. I've called it the 'eclipse function' it is the product of the cosine of the solar zenith angle, the angle between the sun and the zenith overhead, and the portion of the sun obscured by the eclipse. There is a time difference, but only some five minutes – there's a short lag for the ionosphere's movement.

Third, notice that the ionosphere response is not quite symmetric. It rises before the eclipse starts at the path mid point. Speculatively, I wonder if this is a very recently observed phenomenon – a supersonic bow wave travelling ahead of the eclipse. I'll be presenting these results at an upcoming informal HamSCI meeting –looking for comments from researchers.

Zhang, S.R., Erickson, P.J., Goncharenko, L.P., Coster, A.J., Rideout, W. and Vierinen, J., 2017. Ionospheric bow waves and perturbations induced by the 21 August 2017 solar eclipse. *Geophysical Research Letters*, *44*(24), pp.12-067.

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If you recall the map of North America HamSCI stations and recent eclipses, it stopped at Newfoundland. But the April 2024 total eclipse didn't – it ended at sunset over the eastern North Atlantic, as in this map.

It hardly needed any head-scratching for me to realise that most great circle propagation paths from the UK to North America would have their second or third hops within the zone 80% obscured by the eclipse.

Ray trace modelling suggested that 21 MHz, fifteen metres, would be more affected than the lower HF bands, and the band has a decent number of amateurs transmitting WSPR. Top right is for the day before the eclipse – a normal day. This is a heat map, the colour, from blue to red is the number of WSPR reception reports in North America of UK transmitters. Each block is for 20 minutes in time on the X-axis and 200 km in range on the Y-axis. The Y-axis starts at 4600 km and goes out to 7000. The band of yellow, orange and red squares around 5500 km is due to the high number of receivers in New England and New York.

The bottom heat map is for eclipse day. There's a bite taken out. As the eclipse starts we lose spots at the shorter ranges, then the mid ranges, and starting 19:40 there's only one spot received in 20 minutes. The recovery starts, first at the longer ranges, then to mid range, but now, with the sun lower, 15 metres has closed at the shorter range.

Even though the April eclipse was hardly visible from the UK it did have this marked effect on transatlantic radio propagation.

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While the 2023 and 24 eclipses have been major events for HamSCI a continuing strand of research is on Travelling Ionospheric Disturbances or TIDs drawing on amateur radio reception reports.

This example is of a Large Scale TID, with a wavelength over 1600 km and a two and a half hour period. By the way, TIDs with wavelengths shorter than 1000 km are known as Medium Scale.

The top right plot shows how Dr Frissell and colleagues used the great circle ranges of 14 MHz amateur radio reception reports in the Reverse Beacon Network, pskreporter and wsprnet databases to generate this heat map of report counts in two minute and 25 km bins. Time of day is on the Y-axis and distance from 500 to 2500 km on the Y-axis. The authors drew the dotted red line to show that the passing travelling ionospheric disturbance along a radial approximating that in the map, bottom left, modulated the skip zone distance. Near the skip zone, amateurs would have found signals fading in and out over a two and a half hour cycle.

With access to research measurements the authors show in panel D backscatter power at 11 MHz from an ionospheric radar system, again showing modulation of the skip zone.

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It won't surprise you, from my opening slide showing travelling waves in the Strait of Gibraltar, that I've an interest in Travelling Ionospheric Disturbances.

I spotted a lovely example crossing continental North America on 17 May this year. At the centre of the map we have WWV, transmitting precise 10 MHz. The four yellow map pins show HamSCI Grape receiver sites. The small white map pins show the mid point of the paths from WWV to these sites. For each site, the graphs show the Doppler shift on the Y-axis and time UTC from 1600 to 2200 on the X-axis.

All four show wave-like variations. The wave packet is seen earlier at Turn Island, top left, than at N5BRG, bottom right. And the wave packet is seen to decay later at N5BRG than at Turn Island. This *is* a travelling disturbance. The Doppler variation seen at AC0G North Dakota is a little different. What's complicating matters here is that the strongest signal was via the E region, and it does not appear affected by the TID – it is not moving up or down. But we do have short periods with F2 propagation dominating where we can see the TID.

From the start and end times at the four sites, I'd suggest that the TID was moving from north west to south east. But we can do better than that.

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We can estimate the speed of travel of the TID by cross correlating pairs of Doppler traces. First, the magenta path, Turn Island, N4RVE to N5BRG. I take the N4RVE Doppler time series and correlate it with N5BRG at the same time. This gives me a correlation coefficient at time zero. Next, I step the N4RVE record forward by one minute, correlate again, and so on. In the graph we see that maximum positive correlation was with a shift of 27 minutes. The wave packet took 27 minutes to travel from the WWV to N4RVE mid point to the WWV to N5BRG midpoint, a distance of 1360 km, hence a speed of 840 metres per second. We repeat for the orange path, where the maximum correlation was at 35 minutes, which, for a 900 km path, gave a speed of 429 metres per second.

A little vector addition, at the right, gives an estimate of 909 metres per second along a heading of 154 degrees for the TID.

It is possible that this TID was triggered by a near-step change in magnitude of the Auroral Electrojet – current that flows in the ionosphere in the auroral region. When there is a geomagnetic disturbance, as on 17 May, the currents can reach over a million amps. The sudden step in dissipated heat (I squared R Joules per second) is, in a simple analogy the pebble dropping into the pond that gives rise to the TID. The step was at about 15:30 UTC, and knowing the TID speed and direction I could trace back to this estimated source, at about 64 degrees north in the auroral region.

To me, this is a great example of the value to research of a network of amateur radio stations, each with a receiver with GPSDO precision frequency measurement.

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HamSCI encourages contributions to its annual workshop from students and early career researchers. Here are some names, callsigns and brief titles from young people that gave verbal presentations at the single-stream 2024 workshop. In addition, several posters came from this part of the HamSCI community. These young people were not just enthused by their lecturers, it was clear at break times that they were part of a wider, nurturing, community of technical staff and emeritus academics.

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Professor Cathryn Mitchell, M0IBG, Professor of Radio Science at the University of Bath, is a supporter of HamSCI and an associate of our RSGB Propagation Studies Committee. Here are two examples directly related to amateur radio where Professor Mitchell was a supervisor of students studying for the research degree of Doctor of Philosophy. Dr Sam Lo's research and thesis included a study of greyline propagation at 7 MHz using WSPR. And Dr Chris Deacon, G4IFX, has made four presentations at HamSCI events on his research into sporadic E – I'd like to think that the interest and comments Chris received at those HamSCI events provided encouragement from professionals and amateurs alike.

These two theses are salutary reminders that fundamental research on propagation related to amateur radio, even at HF and VHF, is still a hot topic.

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In a post to the HamSCI forum I was guarded enough to write that I saw what *may* have been a solar noise burst on 12 and 10 metres at a few stations in the western United States in December last year at the time of an X5 solar flare. Confirmation from the research community came from this response from Dr Phil Erikson, Director of MIT's Haystack Observatory, having obtained data from his distinguished colleague Dr Alan Rogers. These small peaks in noise received on the amateur systems were indeed from a spectacular radio burst, seen bottom right, where the Y axis is frequency from 40 to 130 MHz, and the colour is noise temperature. As a lone amateur, without HamSCI, I'd have had little chance of getting such immediate confirmation via data from trusted sources.

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Another aspect to HamSCI is that its members work on computer models that help scientists and amateurs better understand the ionosphere. A useful example is the PyLap ray tracing package.

Originally developed as PHaRLAP by Dr. Manuel Cervera and colleagues at the Defence Science and Technology Group, Australia, it was programmed in Matlab – for which hefty license fees are required.

Bill Liles, NQ6Z, a HamSCI member, and an associate of our RSGB Propagation Studies Committee, began work on a python front end for PHaRLAP, subsequently taken on, and completed, by Devin, a Masters student in software engineering at the University of Scranton, due to the initiative of Dr Frissell and financial support from his grants. PyLap is available to all via github.

HamSCI collaborator, Dr Joe Huba, has developed a physics-based computer simulation of the ionosphere – SAMI3 – snapshots of which, through Devin's work, can be used in PyLap instead of the empirical International Reference Ionosphere.

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Here's how, through HamSCI, radio amateurs have helped set out the priorities for space physics research for the next ten years. The US National Academy of Sciences is charged with setting high-level science priorities for the United States. Every 10 years it surveys the community to help set priorities. HamSCI researchers, working with amateurs, submitted two white papers to the survey. The first Amateur Radio: An Integral Tool for Atmospheric, Ionospheric, and Space Physics Research and Operations, discusses the technical capabilities of the amateur radio community and the open scientific questions and space weather operational needs that can be addressed with these capabilities. The second paper, Fostering Collaborations with the Amateur Radio Community, talks about how the professional space science community and the amateur radio community can work together for mutual benefit and provides recommendations for fostering this relationship.

These white papers were distilled into an open access paper – search for "Heliophysics and amateur radio".

This is Citizen Science at its best with amateur radio boldly up front in the titles. For HamSCI members, it starts with a hobby then leads to who-knows-where!

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So how do people get involved in HamSCI? The first thing to do is join our Google group, which now has over 1200 members worldwide. You can do this by visiting hamsci.org and clicking "Join HamSCI."

For papers, articles and posters from HamSCI members, check out our bibliography, and Google scholar will give you a list of key research papers if you search for HamSCI.

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Another great way to get involved is to participate in our regular telecons, which are open to all - **and recorded to YouTube** on the HamSCI channel.

Currently, we have telecons focused on engineering, including the WsprDaemon Grape RX888, on Monday, the Grape (low-cost) Personal Space Weather Station on Thursday, and later on Thursdays, science topics. I’ve shown the current times in UTC.

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My aim today was to share with you how HamSCI connects research and amateur communities. The examples I’ve described could not have happened without substantial grant funding to the research scientists, nor without the enthusiasm, time and dedication of many radio amateurs, transmitters, listeners, designers, builders and coders, especially those I acknowledge, with gratitude, on this slide.

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Thank you. These are links to where you can find out more.