



Astrapi (ΑΣΤΡΑΠΗ) translates to "lightning" in Greek.

Astrapi defines and controls an entirely new field – spiral modulation. Spiral modulation addresses an acute problem - the spectrum crisis. The spectrum crisis impacts four massive market opportunities for Astrapi – satellite, both near-earth and deep space, terrestrial wireless, including 5G+, defense and IoT.

# Validation



**"Definitely interested", Strategic R&D, global defense, commercial space and security systems leader**

**"...it's clear that the satellite industry needs to find a way to deliver more bandwidth with improved cost efficiency"** – CTO, Engineering

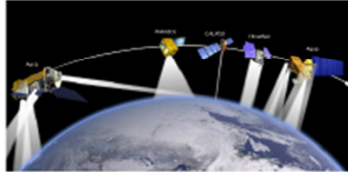
"We recommend you submit a full proposal ...set forth in DARPA-BAA 12-09"

**"Anything regarding the Shannon limit arouses interest"** – VP, Global Sales Engineering

**"We have an on-going interest in spiral-based modulation ...y have a valuable technology with an opportunity to meet the satellite industry's needs."** – VP Integrated Systems, Global VSAT OEM.

**"...anything to reduce stress on bandwidth is of interest..."**– Director of Engineering

**"Very, very interesting...impressive"** – Sales Director, Wireless chip manufacturer



**"I certainly didn't expect to see something like that (spiral modulation) today".** – Office of Naval Research, Program Manager

**"Any who are putting up heavy data signals would be interested"** – Director of Engineering, carrier-grade teleport

**"...spiral-based modulation ...will enable industry to deliver content faster while optimizing the amount of required bandwidth to deliver that content..."** – Director, Signal Exploitation and Geolocation Division

**"We have some possible deep space missions... One of our key areas... is exploring the detection of novel modulation schemes"** – University Professor, Cal Berkeley

**"...problem is the fullness of transponders, especially over the U.S."**

**"...a highly innovative new technique that has the potential to have a big impact in the area of spectral-efficient communications...."** - Technical Advisor, Computing & Communications Division, AFRL Information Directorate

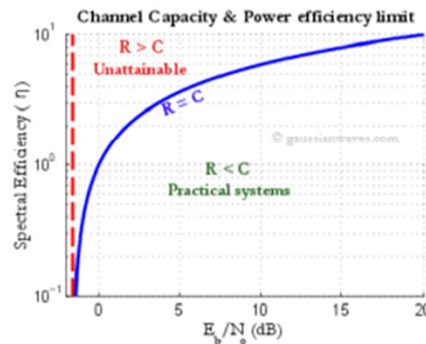
We all know that the amount of spectrum is finite and that the demand for it is not. That's why network operators spent over \$44 billion at the AWS auction which was 2.5X more than what analysts predicted. That's why they spent over \$15 billion at the recent 600 MHz auction. And that is why Astrapi was organized – to alleviate network congestion licensing our spiral modulation. Existing signals are constructed using sine waves with constant amplitude. Astrapi, for the first time, uses spiral modulation with continuously-varying amplitude, continuously-varying amplitude. That's never been done before. There is no prior art here.

# The Shannon Limit



## Assumptions:

- Constant amplitude
- Stationary spectrum



• C.E. Shannon, *A Mathematical Theory of Communication*, BellSyst. Tech. J. Vol. 27, pp. 379-423 and 623-656 (1948)

• C.E. Shannon, *Communications in the Presence of Noise*, Pro. IRE, 37, 10-21 (1949)

Let's do a quick refresh. In the late 1940's, Dr. Claude Shannon, the father of information theory, published "A Mathematical Theory of Communications" and "Communications in the Presence of Noise" the seminal papers that established the capacity of communication channels.

Dr. Shannon's proof uses a Fourier transform, which constructs a signal from sinusoids with constant amplitude over symbol time. The implicit assumption is that the spectrum is stationary.

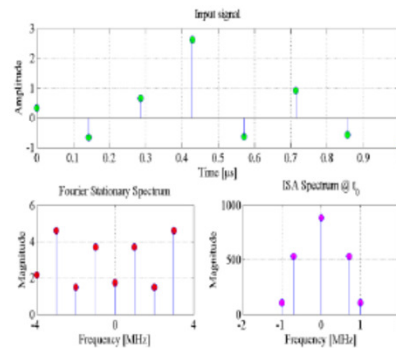
The mathematical model uses complex circles based upon Euler's formula using Fourier analysis. There is a sharp upper bound on spectral efficiency that we've reached. The upper bound is dependent upon the Nyquist rate which is dependent upon the Shannon-Hartley limit. All based upon the assumption that spectrum is stationary and that constant amplitude is used.

# Spiral Modulation



## Spiral Modulation

- Continuously varying amplitude
- Non-stationary spectrum



- J.D. Prothero, *Technical Introduction to Spiral Modulation*, (2017)
- J.D. Prothero., KM Z. Islam, H.D. Rodrigues, J. Barrueco Gutierrez, J. Montalban Sanchez, L. Leonel Mendes, *Instantaneous Spectral Analysis*, (2016)

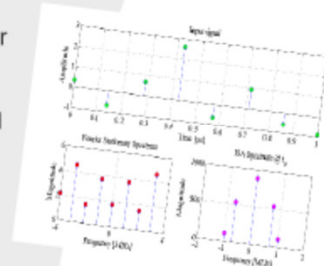
Dr. Jerrold Prothero is the Co-founder and CEO of Astrapi. Dr. Prothero invented spiral modulation while exploring Euler's formula, the foundational math of the entirety of communications. Jerrold was not looking to solve the bandwidth crisis. He was not trying to solve a communications problem. He was exploring the elegance of the math which led to the invention of spiral modulation and the related tools.

Unlike Shannon's assumption of stationary spectrum with constant amplitude, Astrapi enables us to exceed channel capacity, beyond Shannon's law, by introducing spiral modulation using continuously variable amplitude with non-stationary spectrum.

# Instantaneous Spectral Analysis, (ISA)



- ISA converts a sequence of amplitude values - the time domain - into a sum of sinusoids with **continuously-varying amplitude**
- The Fourier Transform (FT) represents an amplitude sequence with sinusoids having constant amplitude, it assumes an evaluation period over which the spectrum is stationary
- The FT effectively averages spectral information over its evaluation period
- ISA is capable of determining **continuously-varying sinusoidal amplitudes at every instant in time**
- For the FT, the maximum rate at which independent amplitude values can be transmitted is equal to the Nyquist rate
- ISA holds an advantage over the FT because Shannon's proof of the sampling theorem, from which the Nyquist rate derives, assumes that the spectrum is stationary over the evaluation interval.



Instantaneous Spectral Analysis (ISA) converts a sequence of amplitude values - the time domain - into a sum of sinusoids with continuously-varying amplitude. This is in contrast to the Fourier Transform, which converts the time domain into a sum of sinusoids with constant amplitude.

Since the FT represents an amplitude sequence with a basis set of sinusoids having constant amplitude, it assumes an evaluation period over which the spectrum is stationary; that is, over which the power assigned to particular frequencies is constant.

The FT effectively averages spectral information over its evaluation period to produce constant sinusoidal amplitudes. ISA is capable of determining continuously-varying sinusoidal amplitudes at every instant in time.

For the FT, the maximum rate at which independent amplitude values can be transmitted is equal to the Nyquist rate. For ISA, there is no inherent upper bound in terms of on the rate at which independent amplitude values can be transmitted. ISA holds this advantage over the FT because Shannon's proof of the sampling theorem, from which the Nyquist rate derives, assumes that the spectrum is stationary over the evaluation interval.

# Summary

- >40 patents issued, pending or filed with PCT coverage
- National Science Foundation (NSF) Phase II grant award (2017)
- "Most Promising Startup", FinSpace Summit for Satellite Finance, Paris, (2017)
- "Grand Prize" SATELLITE 2017 Startup Space (2017), D.C
- EE Times Silicon 60 Emerging Companies to Watch list
- USPTO, Site Examiner Education Program (2017)
- \$2.3m angel funding to-date (seeking \$3 million)
- National Science Foundation (NSF) Phase I grant award (2016)
- National Spectrum Consortium (NSC), accepted member
- Wireless Spectrum R&D committee presenter (2016)
- NAB Futures Park Lab (2016, 2017)
- TIA Startup Challenge Finalist (2016)
- Telecom Council of Silicon Valley award nomination (2015)
- DC I-Corp graduate



We now have over forty patents issued and pending among ten patent families. We are covered in over a dozen countries. We've closed over \$2.3 million in funding and were awarded two National Science Foundation grants totaling over \$923,000. The EE Times recently named us to their Silicon 60 list of emerging companies to watch. We won the inaugural Grand Prize at the Startup Space Pitch at SATELLITE 2017 this past March. In September we were named one of five "Most Promising Startup" at FinSpace, the Summit for Satellite Finance in Paris. And we're a member of the National Spectrum Consortium. They have a billion two-fifty budgeted to optimize defense spectrum and we are well positioned to capture some of that funding.

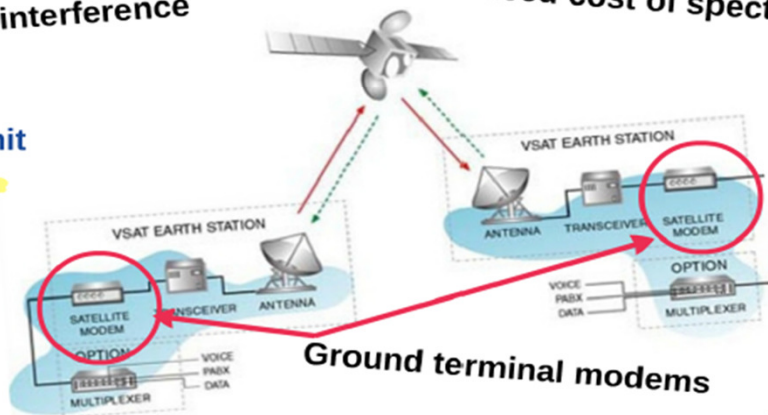
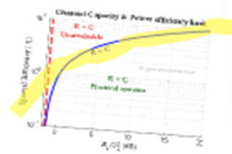
# Market Pain

## Communication channels:

- Capacity constrained
- Power constrained
- Susceptible to interference

- Increased infrastructure CAPEX
- Increased cost of spectrum

## Theoretical Limit



Communication networks and especially satellite networks are increasingly capacity and power constrained, and susceptible to increasing amounts of signal interference. Yet their customers are demanding more. Satellite networks operators, the smart device manufacturers and the modem manufacturers all have a big problem. The modulation approaches they have available have reached the theoretical limit. That's why the operators have to spend billions at the complete opposite end of the value chain to acquire spectrum rights or significantly increase CAPEX on infrastructure to meet this crazy growth in demand.





Well, Astrapi unleashes economic value back down in the physical layer. We compete directly with those existing modulation approaches like Quadrature Amplitude Modulation or QAM, Phase Shift Keying or PSK, and their derivatives.

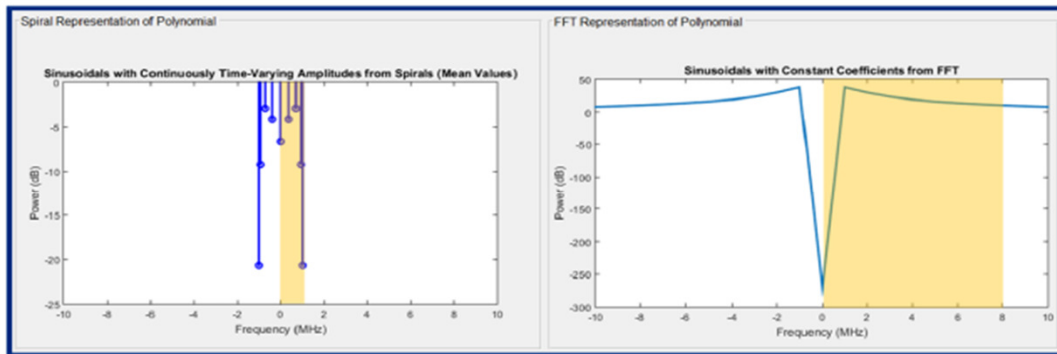
We compete indirectly with alternative infrastructure investment like High Throughput Satellite systems, new cell towers, small cell networks and the repurposing of existing spectrum.

And, of course, there are other emerging approaches. The Microwave Journal recently published an article stating that spiral modulation and full duplex are the two “next frontier” technologies to address spectral efficiency.

We invented and own spiral modulation. Interestingly we were invited to participate in a full duplex defense project with a major prime contractor for a full duplex project. The modulation portion was cut, in fact I’m not sure any of it was funded. The larger point is that Astrapi owns one frontier technology and may be deployed in the second.



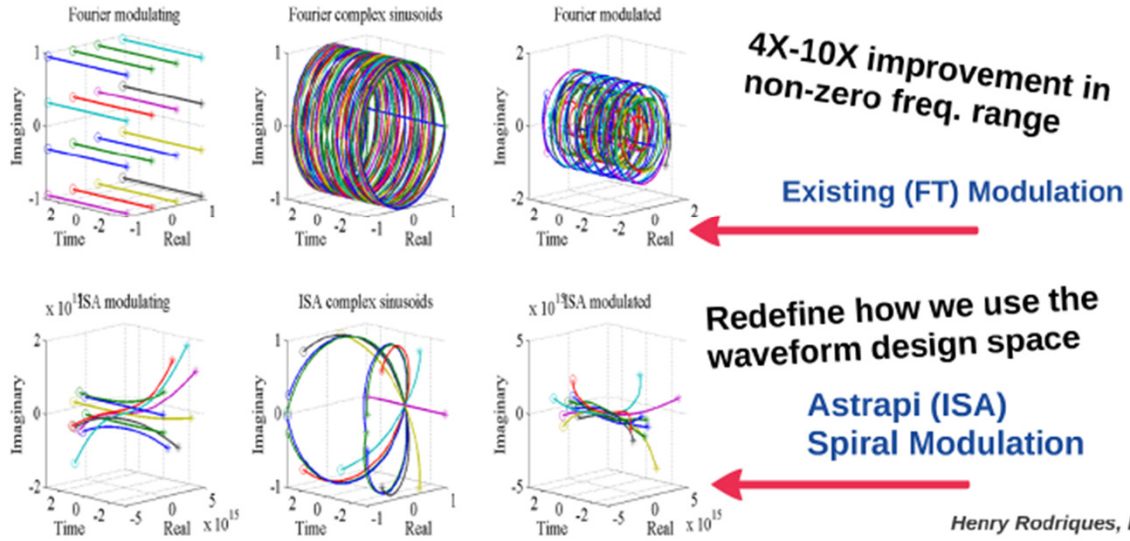
# THE BENEFITS



- Spiral modulation enables:**
- Pack more info into the channel
  - Mitigate coherent interference
  - Extend battery life
  - More precise synchronization

So modulation is all about spectral efficiency first. So what does that mean? If you consider the graphic on the right you will see a traditional modulation example that require 8 MHz to transmit 16 amplitude values per one microsecond of symbol time. Our spiral modulation, on the left, only needs 1MHz. 1MHz to transmit the same 16 amplitude values. Traditional communications theory says this cannot be done.

## Why Astrapi is different...



Henry Rodrigues, Intel

So it's spectral efficiency first, but spiral modulation is much more than that. This graphic was generated by one of our friends in Brazil, Intel. If you compare the lower horizontal graphics to the upper ones you will see that spiral modulation completely redefines how you use the waveform design space and improve the trade-offs among: bandwidth, signal power, data throughput, and error rate.

## Two Applications of ISA



### Waveform Bandwidth Compression, (WBC)



### Spiral Polynomial Division Multiplexing (SPDM)

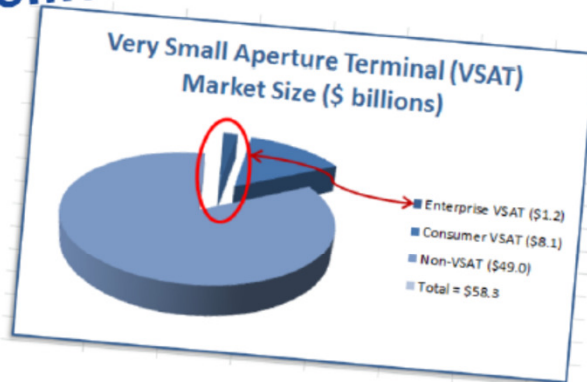


There are two applications of ISA

Waveform Bandwidth Compression (WBC) arises from asking the question: “What is the simplest way to obtain benefits from ISA while changing existing radio architecture as little as possible?” ISA then makes it possible express the data-carrying amplitude values into a much smaller range of frequencies with nonzero amplitude than would be necessary using traditional methods. This has the effect of compressing the waveform bandwidth. In principle, the receiver design is not affected by WBC because the expected sequence of amplitude values arrives, although expressed differently in terms of sinusoidal sums. The diagram on the left shows, at a high level, that we deploy WBC into existing hardware by embedding it before the digital to analog conversion. We don’t think there are any other changes required to network architecture. And we have a couple of operators interested in our approach.

Our National Science Foundation funding is built on the broader deployment of our Spiral Polynomial Division Multiplexing (SPDM). The SPDM model of communication consists of transmitting polynomials. Since general polynomials have much more waveform distinguishability than the sinusoids used by traditional signal modulation methods, they are more resistant to noise, and therefore may have much better Bit Error Rate (BER) performance. SPDM is the combination of representing symbol waveforms as polynomials with ISA for bandwidth-efficient signal transmission.

# Satellite VSAT Segment...



**Service Available Market (SAM)**  
 ~\$60 million - enterprise VSAT  
 ~\$400 million - consumer VSAT  
 ~\$40 BILLION (ANNUAL) - smart devices

## Astrapi Traction

- Southwest Research Institute - partner
- US Patent & Trade Office - (SEE) program
- Wireless Spectrum R&D Committee presentation
- San Diego State University CRADA
- ATSC 3.0 & DVB S-2 R&D "alliances"
- Prospective National Spectrum Consortium prime contract partners
- Major satellite operator/OEM
- DARPA partner - project sequestered.
- Issued, pioneering Intellectual ropor

Our recent National Science Foundation work demonstrated we can reduce the Bit-Error-Rate equivalent and the number of symbols required for standard satellite DVB-S2 framing techniques. In one test we showed about a 5-6 dB performance improvement.

We plan to transition those types of performance gains into the \$58 billion satellite VSAT segment first. The enterprise segment represents a \$60 million opportunity for Astrapi. The consumer VSAT segment represents a \$400 million opportunity. We scale from there. To be clear, we intend to embed spiral modulation into the 2.2 billion smart devices projected to ship annually. That represents a \$40 billion annual, a \$40 billion annual Service Available Market opportunity for Astrapi.

# Use cases

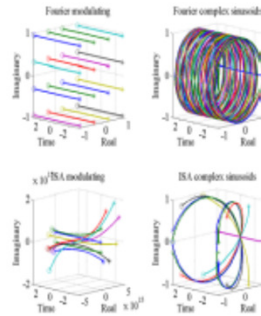


## Satellite VSAT

- Higher throughput
- LEO constellations
- Smaller antennae
- Interference mitigation
- Compete with terrestrial providers

## Terrestrial Wireless (OFDM)

- Power Amplifier
- Interference - adjacent receiver(s)
- Carrier and sample clock offset



## Defense

- Power
- Weight
- Contested channel

## 5G+

Propagation deterioration  
High density interference  
Higher baseband processing  
Network management  
Quality-of-Service (QoS)

**Satellite VSAT**- Goal is to deploy more high-throughput systems, Low Earth Orbit constellations with improved ground station equipment to enable spot beams with reduced antennae size/cost resistant to interference. More transponder capacity, therefore fewer satellites, better interference mitigation improve Quality of Service and reduce guard band requirements, reduce cost and CAPEX to compete with terrestrial high-throughput offerings.

**Terrestrial Wireless** – OFDM, carrier frequency and sample clock offset, interference due to adjacent transmitters due to high channel blocker at the receiver create demodulation and noise performance issues. High Peak-to-Average Power (PAPR) for OFDM signal requires a Power Amplifier that must be oversized in terms of average power which limits applications for laptops, tablets, etc. – it's the battery. A higher degree of accuracy in synchronization with less power enables the SPDM modem to reduce overhead in synchronization signaling. SPDM provides the ability to reduce PAPR of the power amplifier. Aided by SPDM, lower power requirements should enable OEMs to dramatically lower their total cost to manufacture. SPDM minimizes coherent interference performance loss by exploiting dramatically increased waveform design flexibility.

**Defense** – Rifleman Radio, NET Warrior – power/weight/extension of mission, anti-jamming...Same throughput using less power, requires fewer batteries, lessens the load on the soldier, extends the mission life and the novel waveform is hard to find, and through over-sampling resistant to jamming effort. Rogue actors won't know what they are looking. Cognitive radios with AI functionality for defense spectrum sharing applications.

**5G or 5G+** – propagation deterioration at higher frequencies, fat pipe 60 GHz CAPEX real estate challenges, interference due to density, MIMO beamforming needs increased baseband processing capacity all leading to network management quality of service issues...We think spiral modulation is an enabling technology, though we are focused on other uses now.

# The Pathway



## Channel drivers

- Capacity constrained?
- Power constrained?
- Interference issues?
- Defer standards?



## Implementation drivers

- Point-to-Point?
- Fewer symbols?
- Software Defined Radio?
- FPGA?
- High throughput?

## Deployment pathway

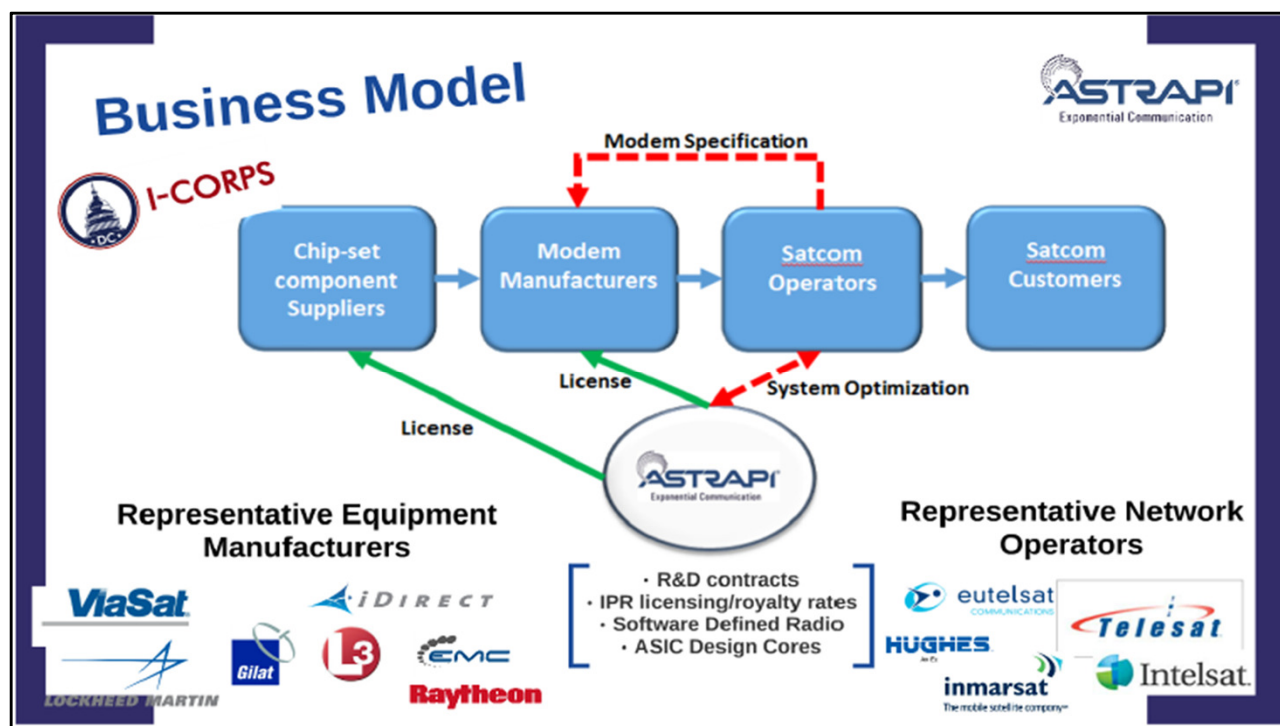
- Enterprise satellite
- Backhaul/fronthaul



So our pathway is broadly defined by channels that are capacity and power constrained and susceptible to increasing interference. That's about all of them really. So we do not want to get mired in standards committee meetings...yet.

That leads us to point-to-point implementations where one entity controls both ends of the channel. Satellite makes sense because they use fewer symbols and the industry is moving to High Throughput Systems to compete with terrestrial competitors. The move to higher throughput requires more power which generates more interference, already an industry problem. We address those challenges. So enterprise satellite makes sense first.





The diversity of satellite networks creates multiple opportunities for Astrapi and is a good market entry point. The diversity of satellite channel requirements enables the modem manufacturers the opportunity to embed spiral modulation into their modems to meet their customer's, the operators, diverse and unique challenges.

So our path to market is to license spiral modulation to the modem manufacturers first. We deploy spiral modulation into Software Defined Radios first. So spiral modulation is a software upgrade first. We scale from there.

Astrapi has traction. We have keen support and interest from a variety of satellite manufacturers and network service providers. We have support from backhaul companies and major defense contractors. We have interest academics, private labs and Defense labs.



## Team



**Jerrold Prothero, Ph.D.**



**Dennis Ahearn**



**Tanay Bhatt, Ph.D.**

### Executive leadership...






### Some of our advisors...






**Ad-hoc Technical Advisors**

- fred harris, Ph.D.
- Bernie Sklar, Ph.D.



**ASTRAPI<sup>®</sup>**  
Exponential Communication

## Research Alliances









## Jury-reviewed events








We are led by Dr. Jerrold Prothero. Jerrold has a background in physics and computer science with honors, as well as an interdisciplinary Ph.D. from the University of Washington. As mentioned he he invented spiral modulation while exploring the foundational math. Dennis Ahearn was the former Chief intellectual property and licensing counsel for Comsat which was acquired by ViaSat and in a similar role with Lockheed Martin. Dennis will tell you we have the strongest IP he has ever seen in his thirty-five year career. Dr. Tanay Bhatt has joined the team and is with us today. He has his Ph.D. in EE and has taught graduate level courses at SMU, UTD, and Arkansas.

We have a strong team in place with a deep bench of advisors. We have deeply talented people who now want to work for us. We now have five global research institutions working with us including the Southwest Research Institute, a \$500 million per year non-profit research center in San Antonio, Dr. fred harris a noted DSP expert out of San Diego State, and Morgan State who is helping us with some machine learning work to ascertain the optimal polynomials to use.

And both the TSR research lab in Spain and Inatel, the national lab of Brazil are helping. We met both at the National Association of Broadcasters show. They are involved in the DVB-S2 and other standards related to video broadcasting.

## Source/Use of Funds



### Sources of Funds

- ✓ • ~\$0.70m NSF Phase II (9/17)
- ~\$3.00m Seed
- ~\$1.65m NSF Phase IIb
- ~\$3.00m Dept. of Defense

### Uses of Funds

- RF Engineers/reference architecture
- Research & Development
  - IPR capture
  - Performance enhancement
- Identify/pursue opportunities
- General & Administrative

NSF = National Science Foundation  
IPR = intellectual property rights

Significantly most of the funds we have sourced will be used to open, staff and support lab in North Texas and capture the intellectual property that falls out of those efforts.

Each problem we solve, each challenge address will likely have an entire patent family fall out of those efforts. Again, there is no prior art here and spiral modulation represents an IP green field.


However, the point here is the value of Astrapi today, tomorrow and twenty years from now resides in our pioneering patent portfolio.

# The Exit


- Softbank buys ARM Holdings \$32bn
- Qualcomm \$8bn annual licensing, \$130bn Broadcom offer, (11/17)
- Cisco, Verizon, Deutsche Telekom, NEA, Khosla invest >\$45m in pre-revenue Kumu























Is there value in IP? Qualcomm generates over \$8 billion annually from their licensing program. Of course Broadcom was trying to buy Qualcomm for over \$100 billion, largely based upon the value of their IP.

ARM Holdings was recently acquired by Softbank for \$32 billion based upon the value of their IP.

Kumu networks, a full duplex, pre-product company has raised over \$45 million and Austin's GenX Communications has secured over \$7 million in funding for their full duplex efforts.

Eight of the ten largest strategic investors, and many, many others, are aligned with our value proposition. So our likely exit is an M&A event based upon the value of our IP.



Exponential Communication

[ Q&A ]

- Astrapi controls a new field: **spiral modulation**
- Spiral modulation addresses: **spectrum crisis**
- Spectrum crisis impacts: **massive markets,**  
(satellite, wireless, defense, & IoT)

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Thank you, I am happy to take questions.